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by

Ronald "J" Booth, Lieutenant, United States Navy

S.B., United States Naval Academy
(1960)

SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE

MASTER OF SCIENCE DEGREE IN MECHANICAL ENGINEERING

AND THE PROFESSIONAL DEGREE, NAVAL ENGINEER

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June, 1967

Signature of Author____
Department of Naval Architecture and Marine Engineering, May 19, 1967

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Thesis Supervisor

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A COMPARATIVE STUDY OF THE HEAVE AND PITCH MOTIONS OF, THE DEEP SUBMERSIBLE, ALVIN AND HER SUPPORT CATAMARAN DURING SURFACE OPERATIONS

by

Ronald "J" Booth, Lieutenant, United States Navy

Submitted to the Department of Naval Architecture and Marine Engineering in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering and the professional degree, Naval Engineer.

ABSTRACT

The heaving and pitching motions of ALVIN and her support catamaran are predicted theoretically and experimentally determined at zero speed by model tests. Comparison is made between theory predictions and experimental results for each of the vessels and then the model test results for the two vessels, with ALVIN in the recovery position are compared.

The theoretical results were computed by a computer program based on the Korvin-Kroukovsky linear theory of ship motions in conjunction with Grim's added mass and damping coefficients. The experimental work with 1/20 scale models was performed at the M.I.T. Ship Model Towing Tank.

It is concluded that theory predictions, correlates reasonably well with model test results for the catamaran. The comparisons for ALVIN were invalidated by questionable experimental data and possible inapplicability of theory. From experimental tests, it was concluded, that the motions of the two ships are synchronous at wavelengths about equal to the length of the catamaran, that the catamaran significantly damps the heave of ALVIN, and that the ALVIN has little effect on the catamaran, in the recovery position. Recommendations for further research in this important part of a "Deep Submergence Vehicle System" are presented.

Thesis Supervisor: Martin A. Abkowitz, Ph.D.
Title: Professor of Naval Architecture

Acknowledgements

The advice and recommendations of many people made this study possible. In particular, the author is grateful and wishes to thank the following persons:

Professor M.A. Abkowitz, who as thesis advisor, provided invaluable technical and editorial guidance, Mr. Frank Omohundro, (Assistant Project Manager, DSRVG, Woods Hole Oceanographic Institution), who provided liaison between the author and Woods Hole Oceanographic Institution, Mr. Arnold G. Sharp, (Mechanical Engineer, DSRVG, Woods Hole Oceanographic Institution), who provided technical assistance on the design and making of the models, Mr. James Sullivan, (Woods Hole Oceanographic Institution), teacher and pattern maker, who constructed the models. His efforts reflect only the highest quality of workmanship, Mr. Hendrik der Kinderen, (M.I.T. Tow Tank Technician), whose invaluable assistance during the experimental work is deeply appreciated, Mr. L. Vassilopoulos and Mr. Frank Sellars, (M.I.T., Department of Naval Architecture and Marine Engineering, Research Assistants), who provided technical assistance in the application and use of the ship motions computer program for the theoretical work, and Miss Susan Johnson, who efficiently typed the manuscript.

This work was done in part at the M.I.T. Computation Center, Cambridge Massachusetts. In addition, the author is grateful to the Graphic Arts Department of Woods Hole Oceanographic Institution for their excellent services.

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CHAPTER I

INTRODUCTION

The deep submergence vehicle is but a component of a larger complex, known as the "Deep Submergence Vehicle System." Next to the submarine, the surface support unit is the most important component of this system. The support unit provides transportation, maintenance, launching and recovery, surface tracking, navigation, and communications with the submarine.

The launch and recovery of the submarine in the open ocean presents a challenging problem to the designer of such a system. The essence of the problem is how to handle the heavy and unwieldy load of the submarine safely and without damage in a seaway.

Wood Hole Oceanographic Institute designed and built a catamaran support vessel (Figure I) during the construction of ALVIN, their deep submergence vehicle (Figure II). The catamaran was equipped with a cradle that could be lowered and raised between the hulls for launch and recovery of ALVIN. This was thought to be the best solution to handling of ALVIN (Dry Weight-13.6 long tons) in a seaway.

During the design of the catamaran several studies were conducted on methods to absorb the shock expected on initial contact between the submarine and catamaran cradle. Because initial trials on launching and recovering a dummy ALVIN in a seaway, revealed that the expected shock did not exist, these studies were not implemented.

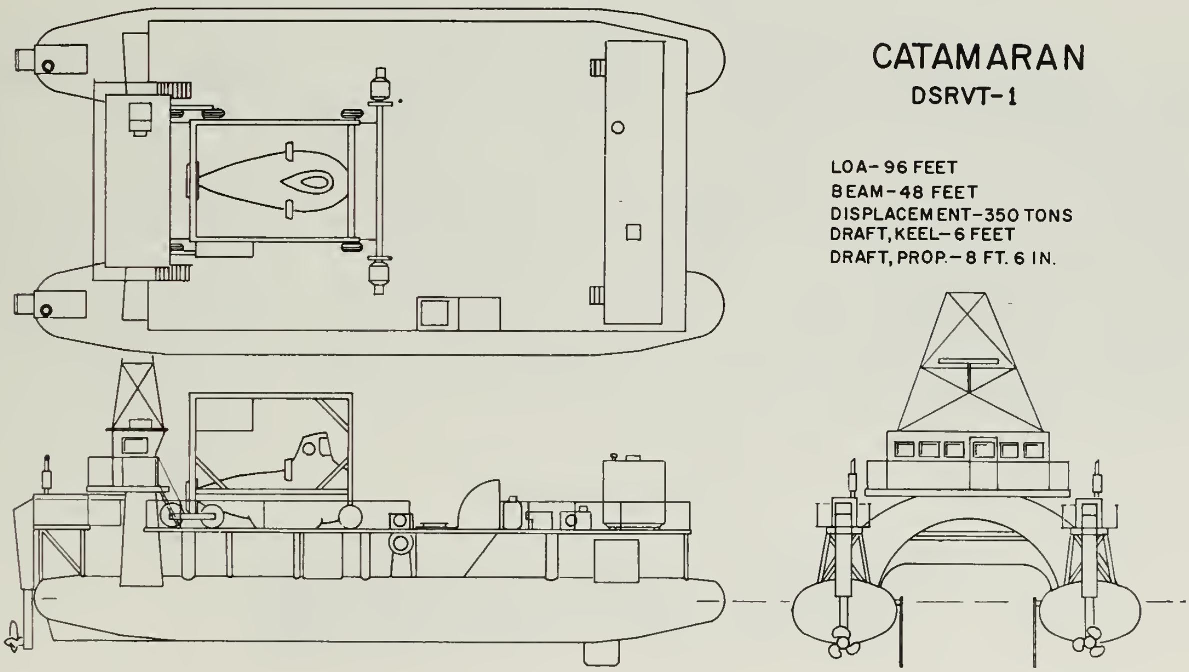
The catamaran concept has proven itself as an extremely successful support vessel in the open ocean. It was able to launch and recover ALVIN in up to

state 4 seas and to be a stable and seaworthy vessel in 25-ft seas[15].

Two main objectives comprise the scope of this investigation. The first is an evaluation of the accuracy of linearized theory of heaving and pitching motions of ALVIN and the catamaran by comparing theoretical computations to experimental model motion data under similar conditions. The second was to compare the ALVIN model motion data with the catamaran model motion data in the recovery position.

The conclusions from this investigation may prove useful in the future design of a "Deep Submergence Vehicle System."

FIGURE I

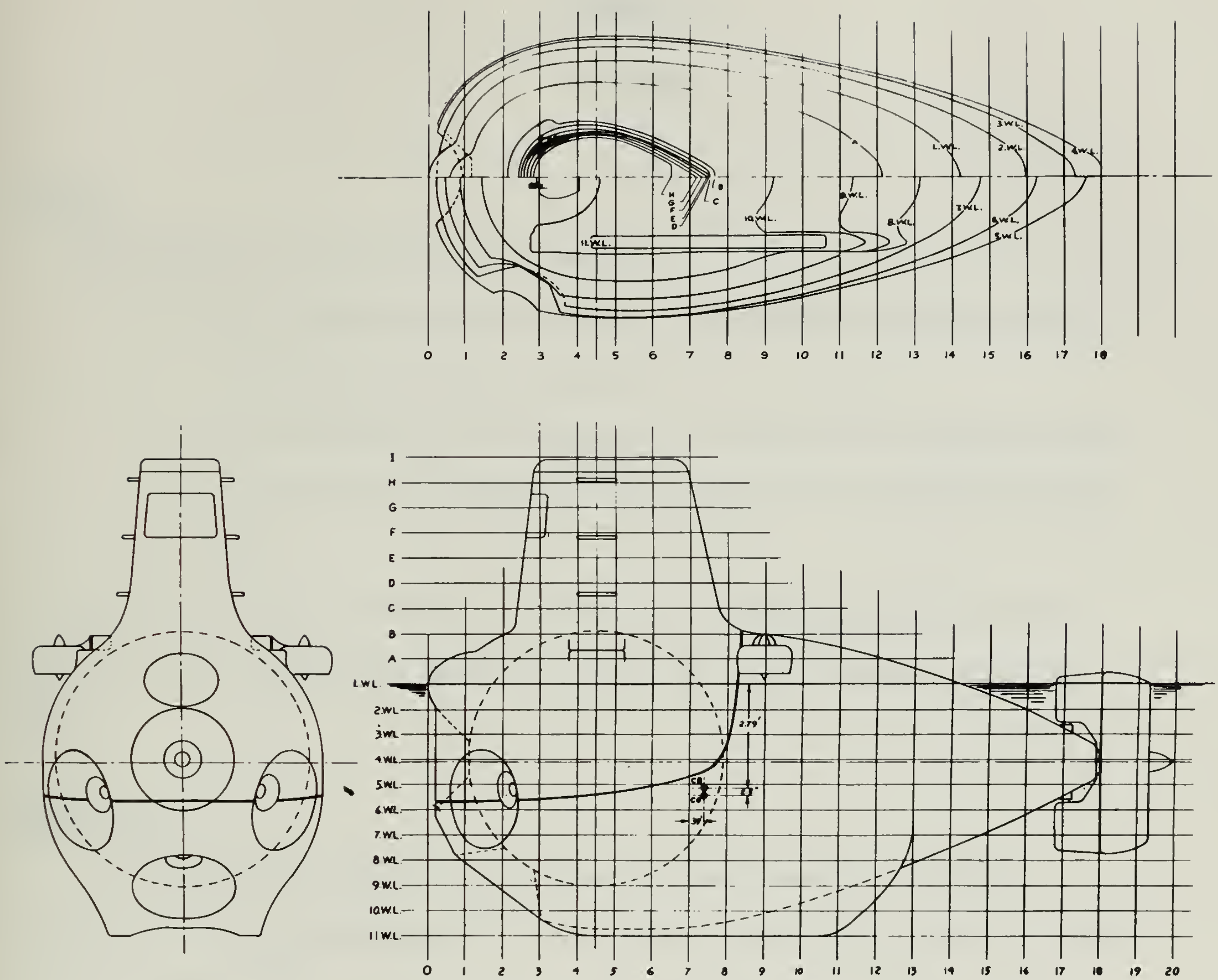


CATAMARAN OUTBOARD PROFILE

(APPENDAGES WERE NOT MODELED)

(Fig. 16 in "ALVIN, 6000 FT. Submergence Research Vehicle")
by Mavor, etc.
SNAME, 1966

FIGURE II



ALVIN HULL LINES

APPENDAGES WERE NOT MODELED, BUT PROPELLOR SHROUD AND EXTERNAL BOUYANCY BLOCKS (NOT SHOWN) WERE MODELED.

(Fig. 8 in "ALVIN, 6000 FT. Submergence Research Vehicle")
by J.N. Mavor, Froehlich, Marquet, Rainnie
SNAME, 1966

CHAPTER II

PROCEDURE

General

This study was conducted by two methods:

1) the theoretical computations of heaving and pitching motions of ALVIN and of the catamaran.

2) the experimental investigation of heaving and pitching motions of ALVIN and catamaran models in the M.I.T. Ship Model Towing Tank.

Presented in this section are the various assumptions and procedures utilized in the theoretical computations and the tests conducted with the models.

Theoretical

The theoretical computations were based upon linear strip theory developed by Korvin-Kroukovsky[3] in conjunction with Grim's results on added mass and damping[16]. This theory has been utilized in a digital computer program developed at the M.I.T., Department of Naval Architecture and Marine Engineering by Haslum and Vassilopoulos[7]. The analytical details of this linear theory as utilized in the computer program are summarized in Appendix B from reference (7). Use of this computer program, described in Appendix C, was made for the theoretical computations.

The basic input information required for ships to the computer program is the;

1) number of stations, length, and displacement

2) maximum beam, sectional area coefficient, and draft for each station

3) radius of gyration, and longitudinal location of center of gravity

The assumptions made in order to submit ALVIN and catamaran input data were;

1) catamaran represented as a single hull with half the displacement of the catamaran. Equivalent to assuming no hull interference.

2) the maximum beam for both ships occurred at the waterline for both ships

3) ALVIN's shrouded propellor was represented as a solid disk

4) submerged stations immediately forward of the shroud were entered as if a vertically solid up to the waterline from the maximum beam.

The input information for waves to the computer program was:

1) wave amplitude -0.125 ft., 2.5 ft. full scale

2) shortest wavelength -.75 ft., 15 ft. full scale

3) longest wavelength - 10 ft., 200 ft. full scale

4) increment steps from shortest to longest wavelength -0.25 ft., 5 ft. full scale

5) speed of ship -0.0

The computer output was, for each wavelength to shiplength ratio, the frequency of encounter, the heave amplitude (ft.), the heave amplitude non-dimensionalized with wave amplitude, the pitch (degrees), the pitch (radians) non-dimensionalized with the maximum wave slope, $2\pi/\lambda\ h_o$. In addition,

although not used in this investigation, the relative bow motion, the cosine component, the sine component, and phase angle were outputs.

This investigation was conducted for zero forward speed of ALVIN and the catamaran corresponding to the launch and recovery conditions of the system.

Experimental

The experimental investigation was conducted in the M.I.T. Ship Model Towing Tank equipped with a hydraulic wave generating system.

The tank is rectangular in cross section, 108 ft. long, 8 ft. 7 in. wide with a normal water depth of 4 ft. An electrically driven carriage is used for a point of model attachment and has an instrument patch panel for connection to the recording equipment. A beach at the opposite end from the wave generating equipment essentially eliminates wave reflection.

The waves are generated by the motion of a paddle at one end of the tank, which rotates about an axis at the tank bottom. The paddle fills the full width and depth of the tank. The paddle is powered by a high pressure hydraulic ram and the motion is controlled by an electronically controlled servo valve. For generating a train of regular waves of a given length, a sinusoidal signal from a previously prepared magnetic tape is the input to the wavemaker control system where the desired wave amplitude is set by a potentiometer reducing the 5 volt peak-to-peak sinusoidal signal. A more complete description given by Pearlman may be found in Reference (4).

The model dimensions were a compromise governed by the following requirements:

1) To allow the testing together of ALVIN and catamaran, the model scales had to be equal

2) It was desirable to make the catamaran model less than 5 ft. for transportation and handling

3) The ALVIN model should be as large as possible to accommodate the weight of instrumentation

The scale chosen was 1/20 the full scale size.

The full scale and model particulars are listed in Table I.

TABLE I

Full Scale and Model Particulars

Scale = 1/20

	Item	Full Scale	Model
C	Length, L, ft.	96.0	4.8
A	Beam(overall), ft.	48.0	4.8
T	Beam(each hull), ft.	14.0	0.7
A	Draft, T, ft.	6.0	0.3
M	Displacement, tons	352.5 (SW)	0.0436 (FW)
A	Longl. C.G. aft.		
R	of F.P., ft.	48.0	2.4
A	Longl. radius of		
N	gyration, ft.		0.91
A	Length, L, ft.	22.0	1.1
L	Beam, ft.	8.25	0.4125
V	Draft, T, ft.	7.07	0.354
I	Displacement, tons	13.6 (SW)	0.001658 (FW)
N			0.00215 (FW) due to approx. in actual model
	Longl. C.G. aft. of F.P., ft.	8.54	0.469
	Longl. radius of gyration, ft.		0.242

The instrumentation used to measure wave height, pitching motion amplitude, and heaving motion amplitude is now described.

<u>Wave Height</u>

During the author's use of the tow tank, the sonic wave probe, which is the usual means of measuring wave height, was out of commission. The wave height was measured by a two wire resistance probe that was extended to half depth in calm water. The two wires, spaced approximately 1 in. apart with the water completing the circuit, is one half of a resistance bridge with the other half of the bridge in the carrier preamplifier. The varying water height, as a wave passes the probe, changes the resistance of the bridge providing an electric signal proportional to the change in water level. The electrical signal is the input to the oscillograph recorder, thus providing a continuous record of the wave system. The probe was linear for ±1.5 in. of water level change and, with a scale of 10 mm/in, the oscillograph recorder had an accuracy of less than ±0.25 mm or within 2.5%.

<u>Pitching Motion Amplitude</u>

The pitch angle record was obtained using a pitch bearing mounted in the pitch bearing block which is rigidly attached to the model. A rotary variable differential transformer coil is attached to the bearing block. The core is attached to and rotates with the bearing. Thus the angular motion of the model about the point of attachement generates a signal in the coil which is proportional to the pitch angle and is another input to the oscillograph recorder. This provides a continuous record of the pitching motion as a function of time.

Heaving Motion Amplitude

The vertical oscillations of the model were measured by a linear variable differential transformer. The core was within an aluminum rod, which was attached to the model. The rod passes through a ball bearing guide, which was attached to the carriage, and contains a three winding coil.

A heave rod mounted securely in the pitch bearing and passing through a ball bearing guide attached to the carriage, served the purpose of allowing vertical motion only, while the pitch bearing permitted pitch angular rotation only. For the catamaran model; the heave rod was square in cross section as was its guide, to restrain the model from other motions, especially yaw. For the ALVIN model; the tubular heave rod had, at its upper end, a vane that rode in a teflon slot on a teflon bearing, to restrain the model from other motions. The linearsyn core rod is fixed to the heave rod with a plexiglass bracket and thus follows the vertical motions of the model. The linearsyn differential transformer generates a signal proportional to the vertical motion of the model and, as another input to the oscillograph recorder, provides a continuous record of the heaving motion.

Figure III is a picture of the catamaran model showing the instrumentation and Figure IV is a picture of the ALVIN model showing the instrumentation. Table II lists the instrumentation weights. Figure XXV is a typical oscillograph recording tape that was used for data collection.

The models were ballasted to the correct draft with the instrument weights. Then the ballast was shifted to adjust for the longitudinal radius of gyration. The procedure used to determine the model radius of gyration is described in Appendix D.

FIGURE III

CATAMARAN MODEL INSTRUMENTATION

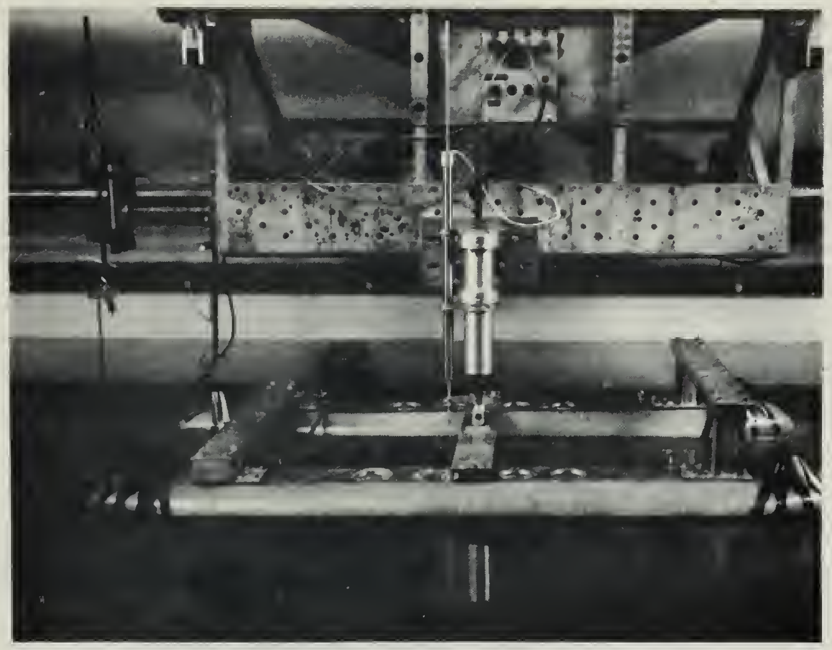


FIGURE IV

ALVIN MODEL INSTRUMENTATION

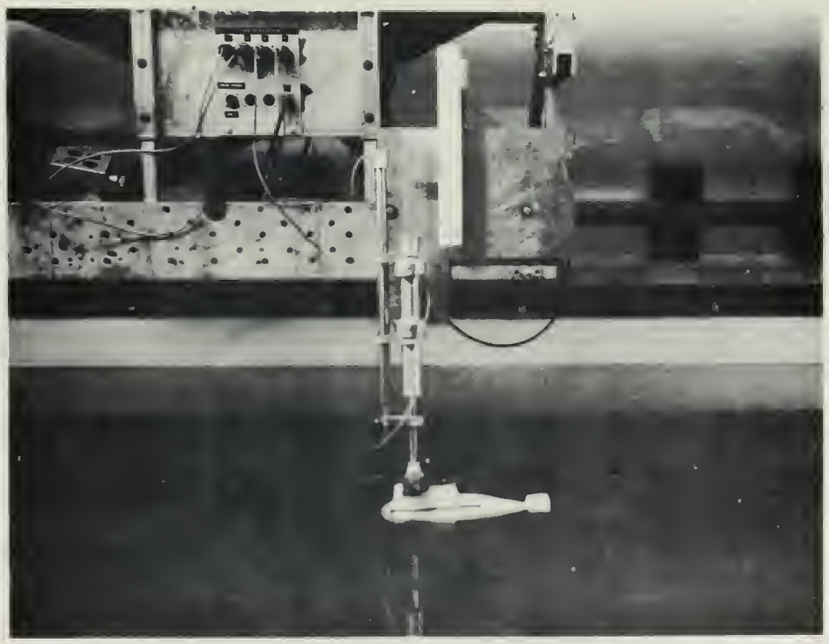


TABLE II

Instrumentation Weights

Model	Item	Weight (lbs)
Catamaran	Heave Rod (Solid)	2.36
	Pitch bearing block, bearing, and mounting bolts	.71
	linearsyn core rod and bracket	.385
	Total	3.455
ALVIN	Heave Rod (Hollow)	.105
	Pitch heaving block, bearing, and mounting bolts	.71
	linearsyn core rod and bracket	.385
	Total	1.19

Test Procedure

To determine the heave and pitch response of ALVIN and the catamaran, they were first tested separately and then both models together with ALVIN in the recovery position between the catamaran hulls. The runs that were conducted are listed in Table III.

All runs were conducted with the carriage 30 ft. away from the wavemaker paddle to ensure regular waves. With the calibrated wave height probe, on the carriage, and no models in the water, the wave amplitude settings on the potentiometer were determined for each wavelength.

The catamaran model was tested for two different wave amplitudes at each wavelength. A single catamaran hull was then tested in the same manner. Because of the bow and stern symmetry of the catamaran, all runs were for both directly ahead and astern seas. The ALVIN was tested in directly ahead and directly astern seas.

For testing together, both models were attached to the carriage with the heave rod and pitch bearing. This allowed both models to move freely in vertical motion and in pitch angular rotation. The first set of runs were with heave and pitch instrumentation on ALVIN. The second set of runs were with the heave instrumentation on the catamaran while the pitch instrumentation on ALVIN. This method of attachment is shown in Figures V and VI.

TABLE III

Experimental Runs

Model	Wave Amplitude (ft.)	Wavelength (ft.)
Catamaran	0.0625 0.125	3.0, 4.0, 4.5, 6.0, 10.0 3.0, 4.0, 4.5, 6.0, 10.0
Catamaran (Single hull)	0.0625 0.125	3.0, 4.0, 4.5, 6.0, 10.0
ALVIN, ahead seas	0.0625	1.0, 2.0, 3.0, 5.0, 10.0
ALVIN, astern seas	0.0625	1.0, 2.0, 3.0, 5.0, 10.0
ALVIN, Recovery Position, ahead seas	0.0625	1.0, 2.0, 3.0, 5.0, 10.0
ALVIN, Recovery Position, ahead seas, pitching only	0.0625	3.0, 4.0, 4.5, 6.0, 10.0
Catamaran, Recovery heaving only	0.0625	3.0, 4.0, 4.5, 6.0, 10.0

FIGURE V

RECOVERY POSITION MODEL INSTRUMENTATION

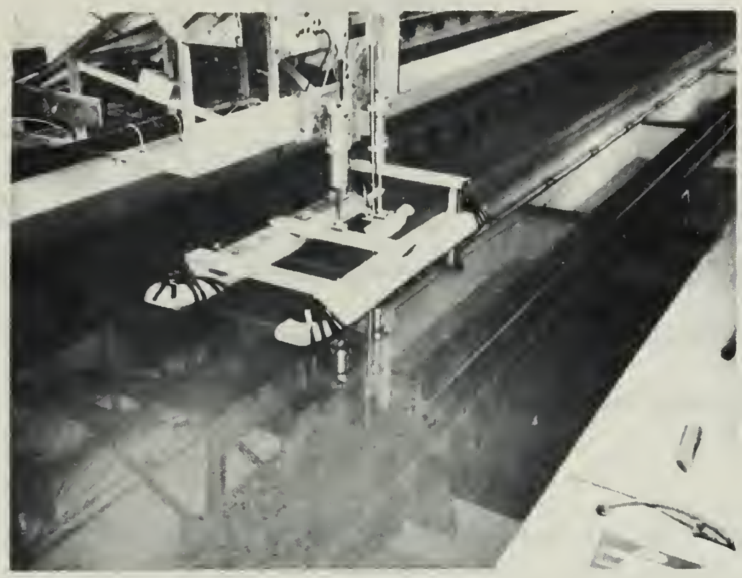
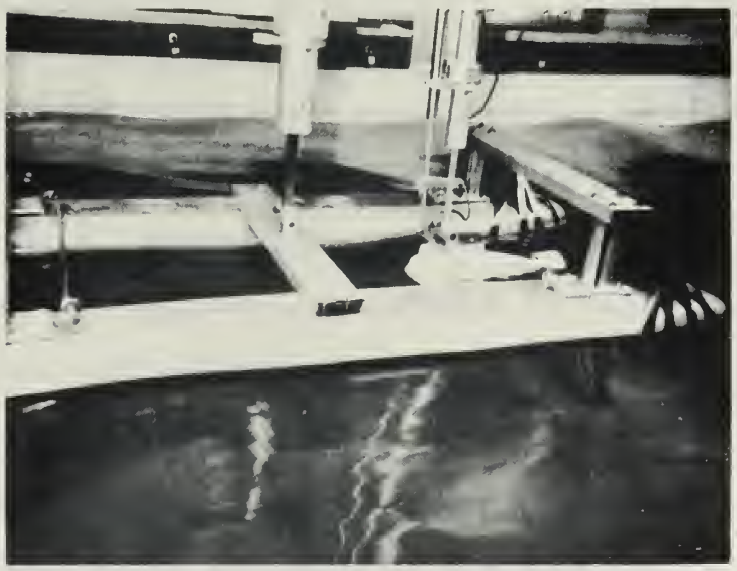


FIGURE VI

RECOVERY POSITION MODEL IN WAVES



CHAPTER III

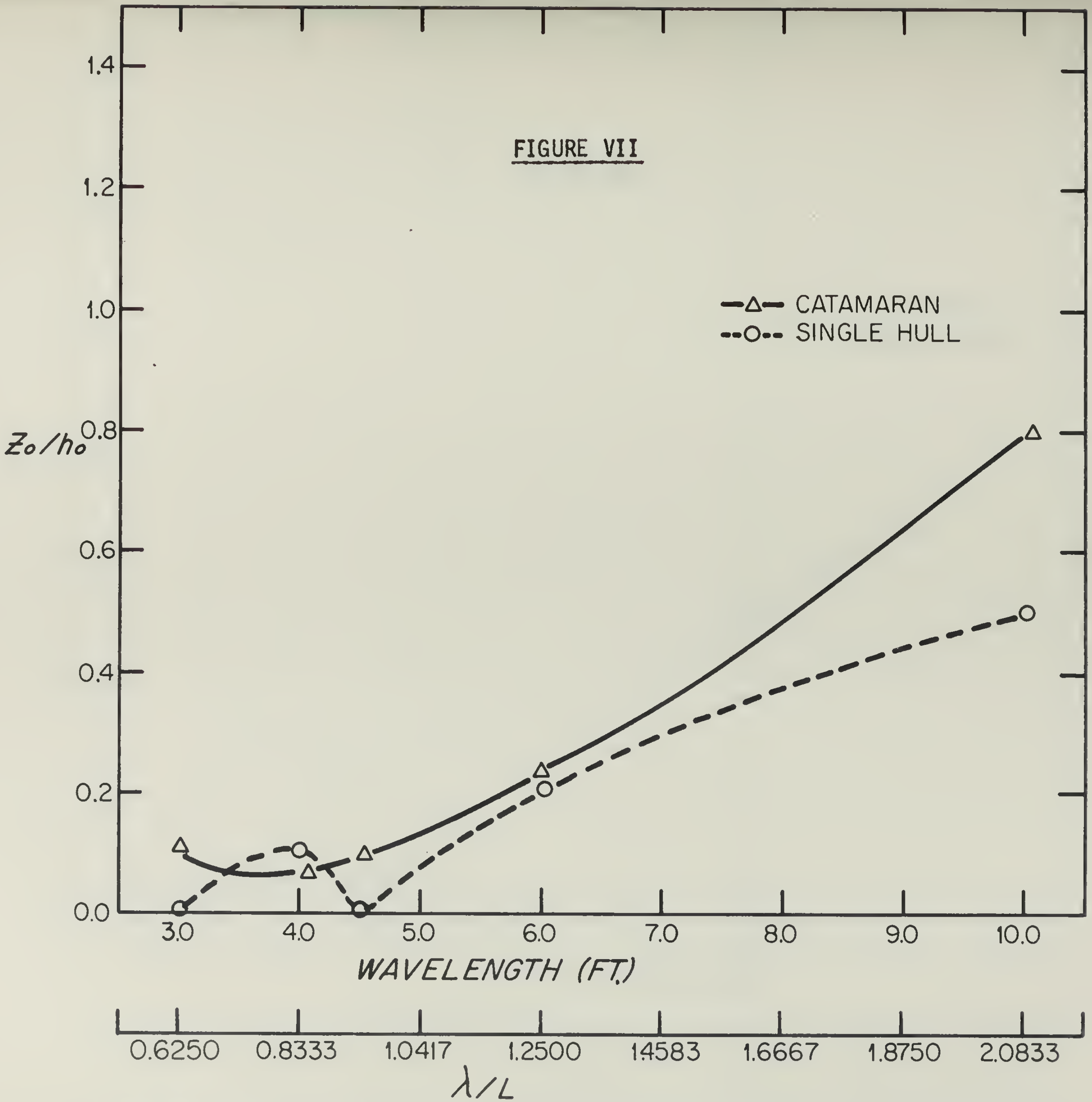
ANALYSIS

The theoretical computed results for the catamaran were for a single hull only. There is no known way for the Korvin-Krovskovsky linear strip theory to take into account two hulls as in a catamaran configuration. Either the assumption must be made that no interference exists between the two hulls or a correction must be made.

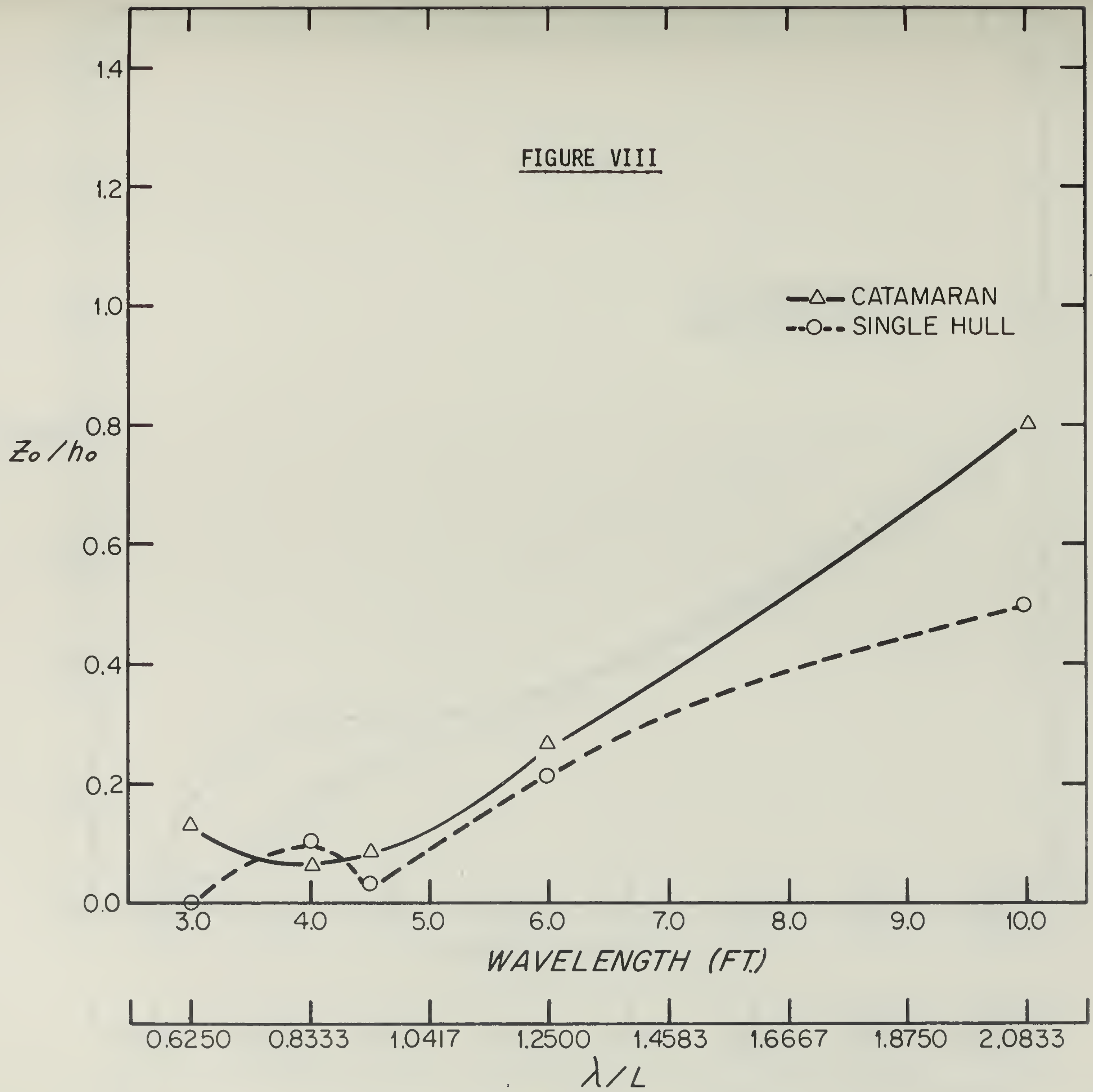
The damping of heaving and pitching motion is caused by the oscillating body generating a traveling wave system in which energy is dissipated (2). With two hulls in close proximity to each other and both oscillating, there must be interference between the hulls. Therefore it would be erroneous to make the assumption of no interference and accordingly a way to correct the theoretical results was sought.

Because there was no theory available, empirical methods were the only means available and the procedure used to correct the theoretical results is described herein.

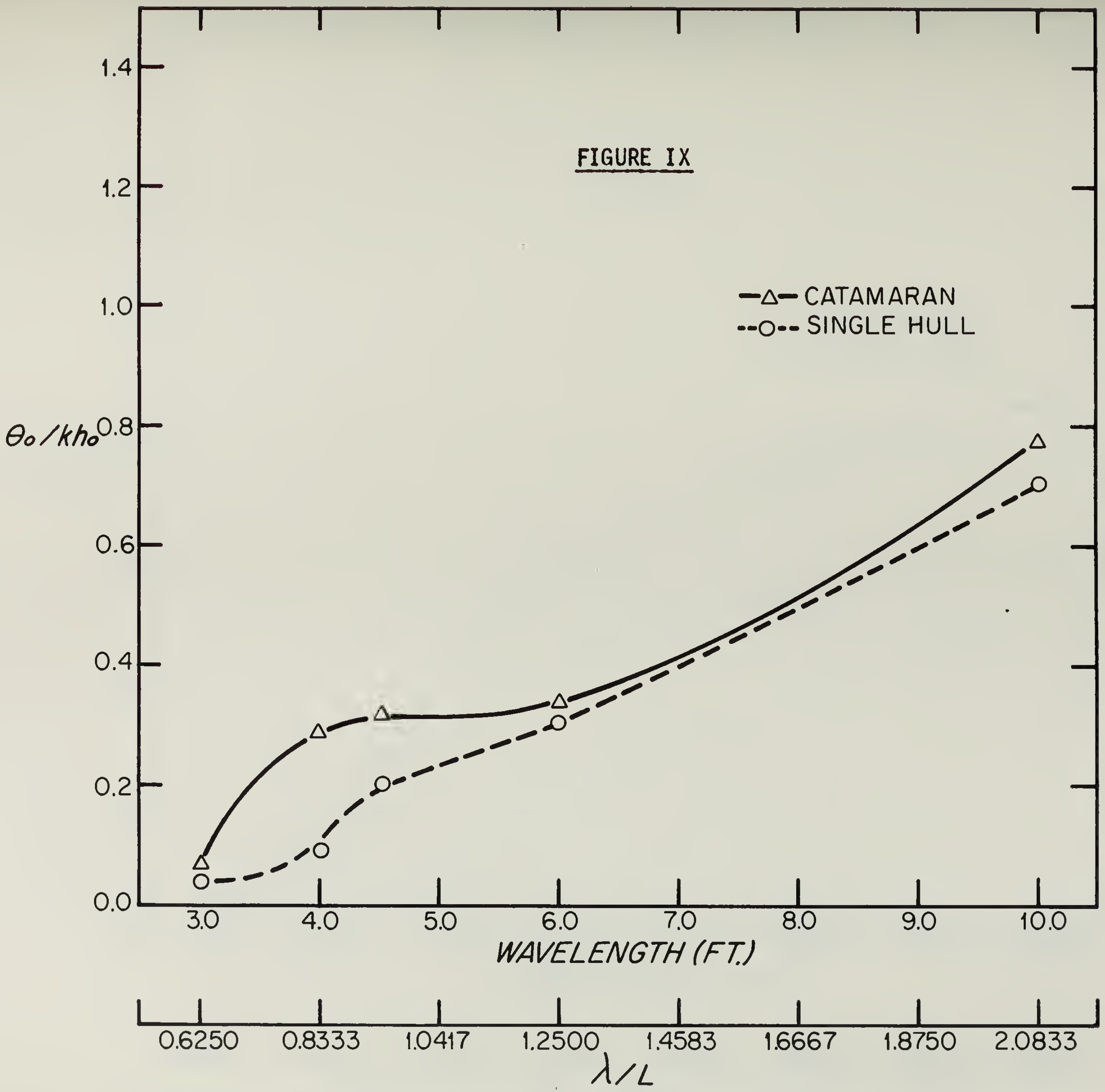
The non-dimensional experimental heave and pitch motion amplitudes for the catamaran and a single hull were plotted for two different wave heights, (Figures VII, VIII, IX, and X.) From the data obtained for the two different wave heights, at each wavelength, a mean value was obtained by interpolation for both the case of the single hull and the catamaran. These points are plotted in Figures XI and XII. The ratio of the catamaran to the single hull was computed for the different wavelengths and applied as a correction to the theoretical non-dimensional motion amplitudes for the single hull. (See Table IV).



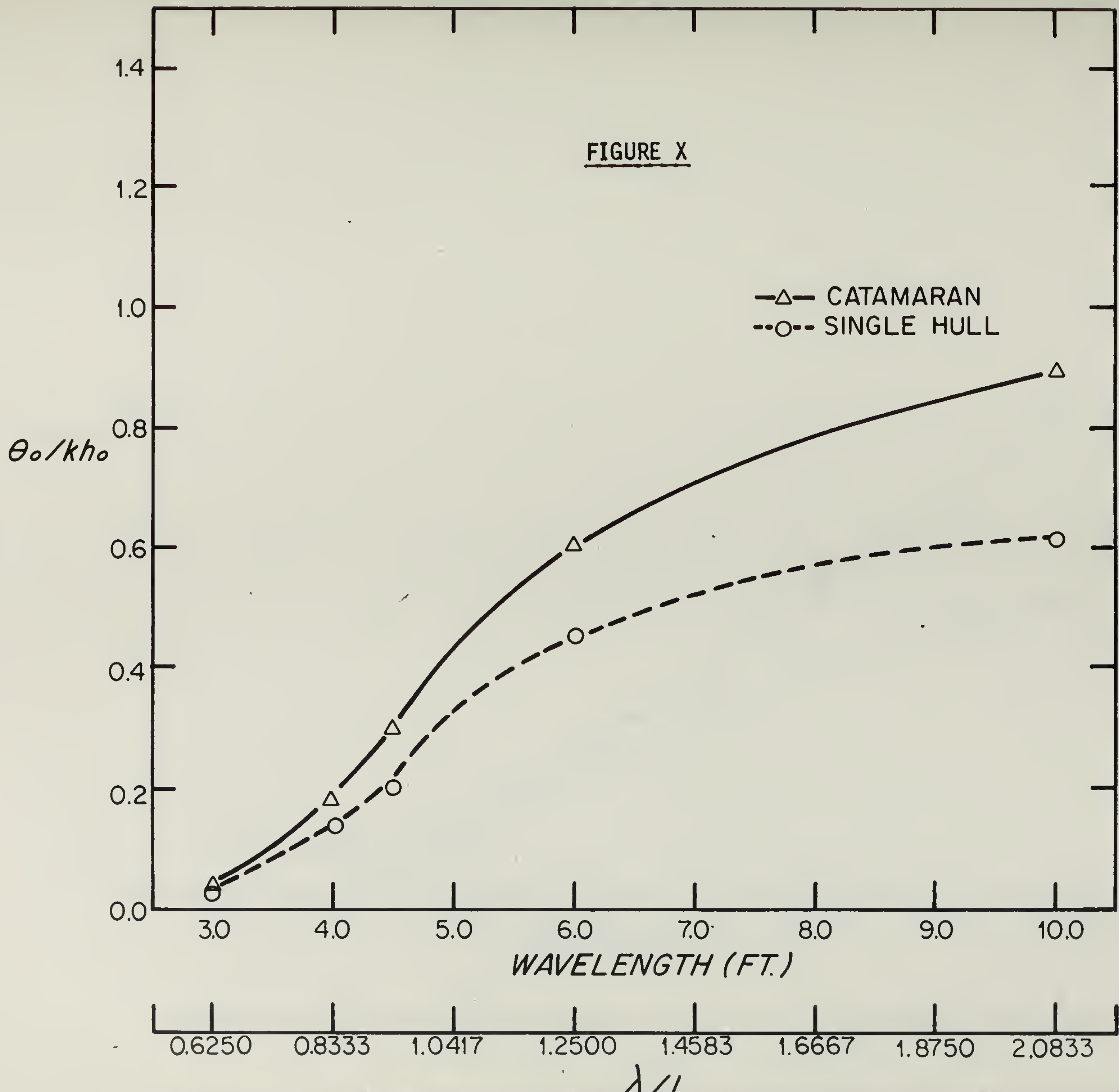
SINGLE HULL OF CATAMARAN AND CATAMARAN MODEL EXPERIMENTAL HEAVE AMPLITUDE, ho = 0.375 in.



SINGLE HULL OF CATAMARAN AND CATAMARAN MODEL EXPERIMENTAL HEAVE AMPLITUDE, ho = 0.75 in.



SINGLE HULL OF CATAMARAN AND CATAMARAN MODEL EXPERIMENTAL PITCH AMPLITUDE, ho = 0.375 in.



SINGLE HULL OF CATAMARAN AND CATAMARAN MODEL EXPERIMENTAL PITCH AMPLITUDE, ho=0.75 in.

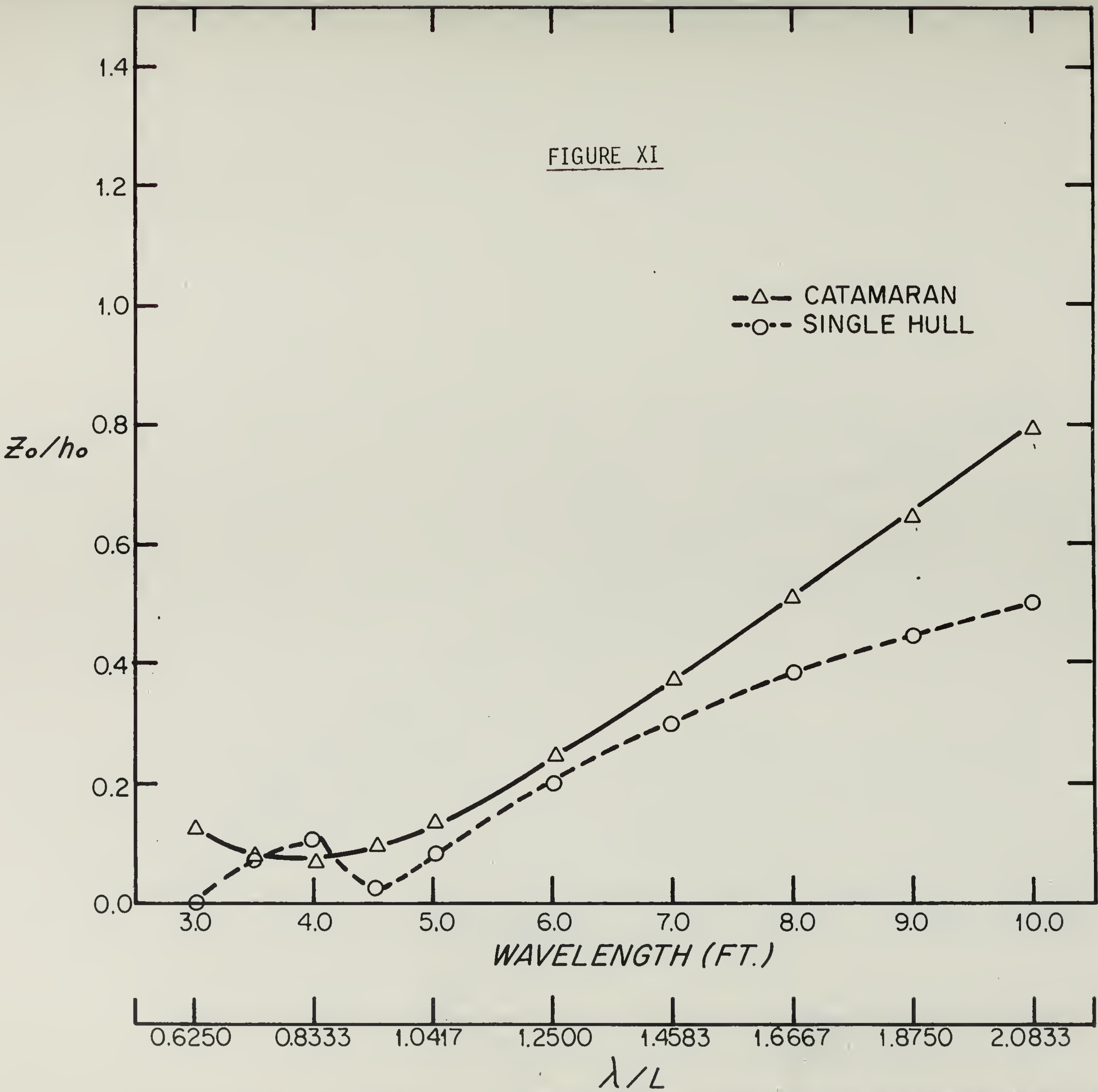
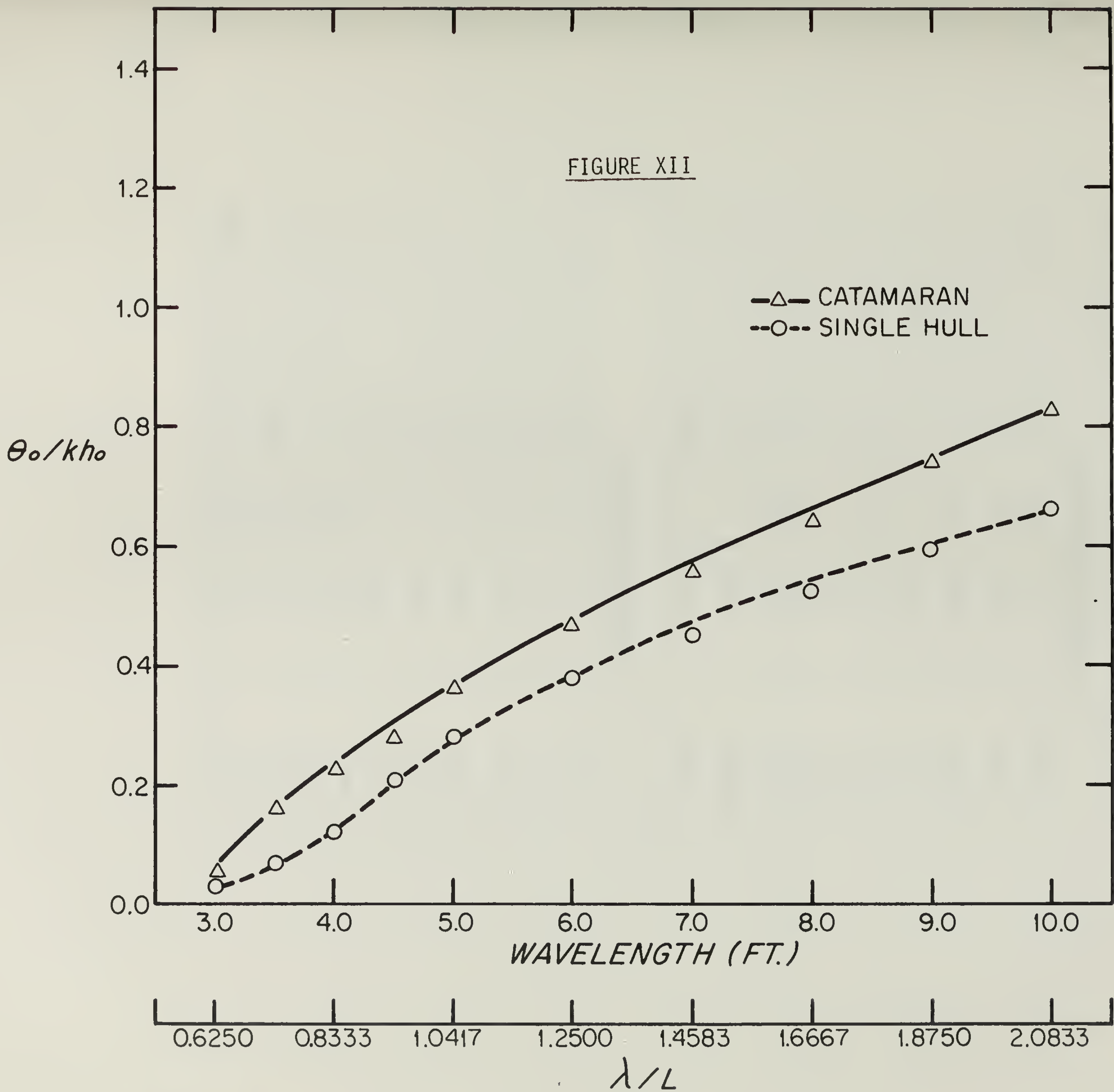


FIGURE XI

SINGLE HULL OF CATAMARAN AND CATAMARAN MODEL EXPERIMENTAL MEAN HEAVE AMPLITUDE



SINGLE HULL OF CATAMARAN AND CATAMARAN MODEL EXPERIMENTAL MEAN PITCH AMPLITUDE

TABLE IV

Correction for Single Hull to Catamaran

λ(ft)	Mean Single	Mean Cat.	Cat. Single	Theory	Corrected Amplitudes
			(heave amplitude)		
3.0	0	.1200	+.1200	.2611	.3811
3.5	.0700	.0750	1.072	.2553	.2735
4.0	.1034	.0667	0.645	.1488	.0960
4.5	.0200	.0917	4.58	.0169	.0775
5.0	.0800	.1300	1.625	.1115	.1815
6.0	.2083	.2500	1.2	.3244	.3895
7.0	.3000	.3700	1.232	.4769	.5880
8.0	.3800	.5050	1.33	.5914	.7860
9.0	.4425	.6500	1.47	.6729	.9880
10.0	.5000	.8000	1.6	.7335	1.172
			(pitch amplitude)		
3.0	.0300	.0501	1.67	.0499	.0749
3.5	.0650	.1600	2.42	.0536	.1300
4.0	.1200	.2245	1.87	.1645	.3080
4.5	.2025	.2755	1.31	.2689	.3525
5.0	.2750	.3625	1.32	.3608	.4760
6.0	.375	.4687	1.25	.5060	.6325
7.0	.4525	.5550	1.228	.6098	.7480
8.0	.5250	.6475	1.232	.6848	.8430
9.0	.5950	.7400	1.242	.7401	.9200
10.0	.6590	.8320	1.262	.7818	.9850

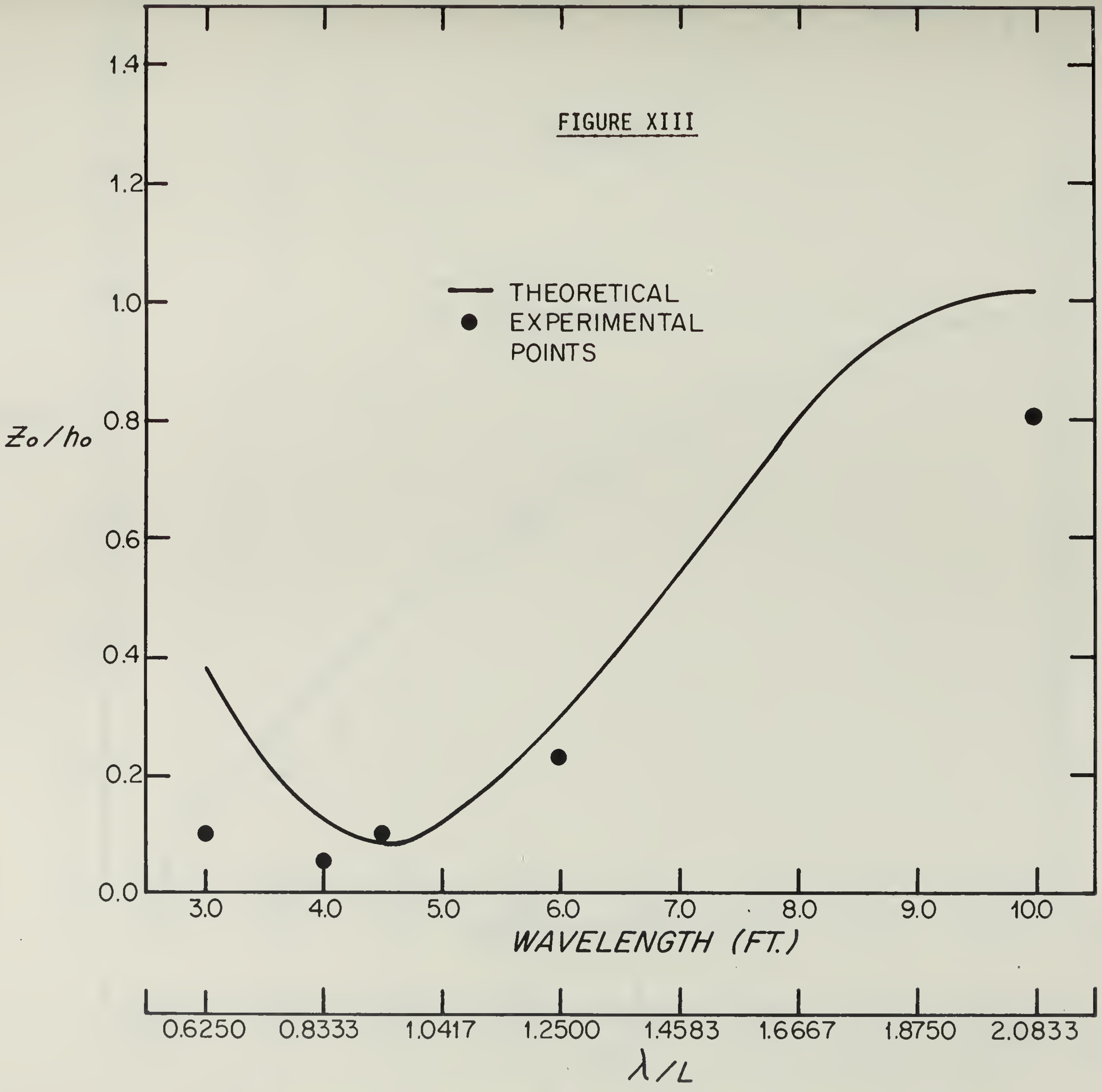
CHAPTER IV

RESULTS

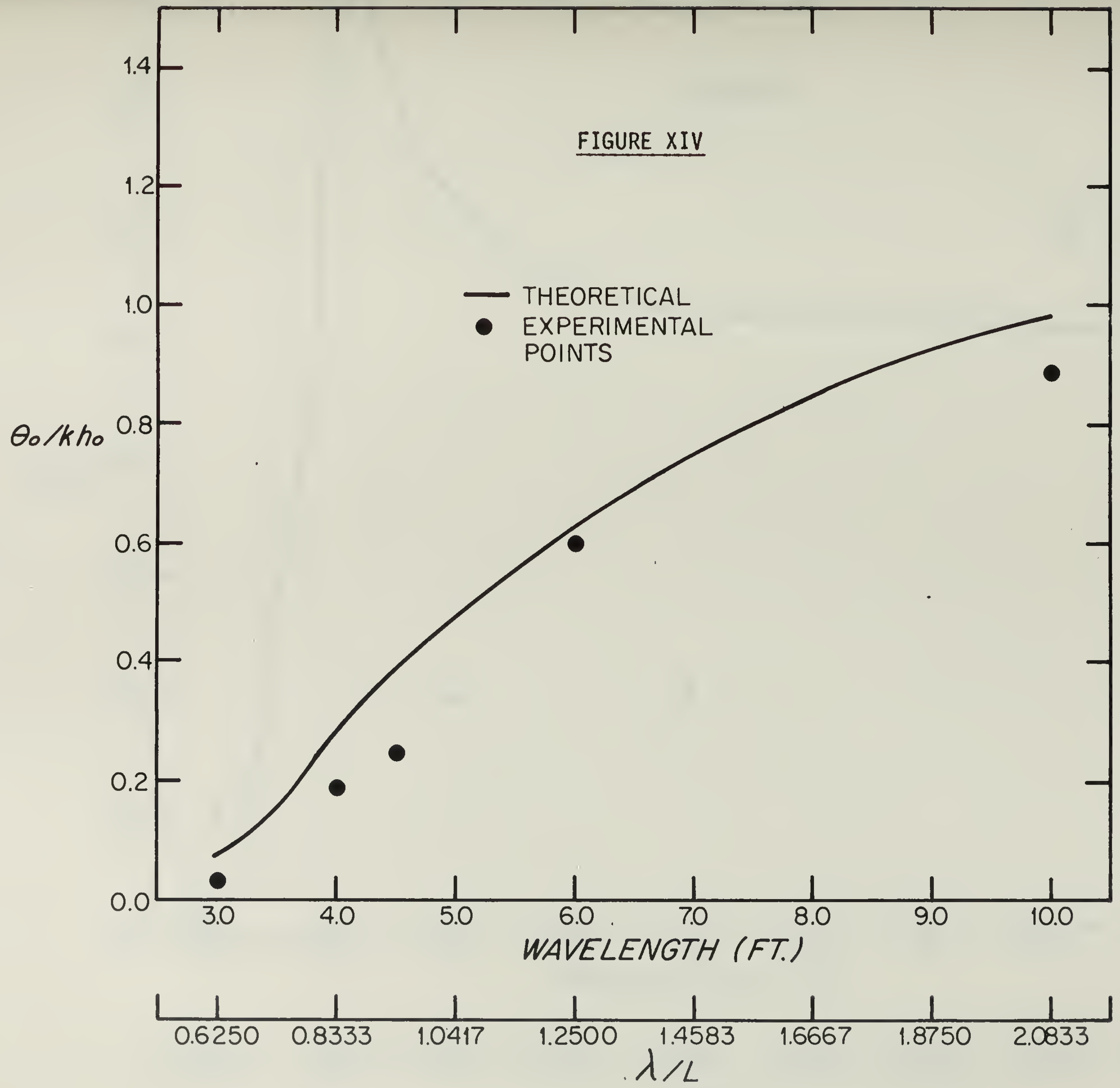
The results are presented in the form of non-dimensional motion amplitudes versus wavelength and wavelength to shiplength ratio, Figures XIII-XXIV. Heave, z_o, is non-dimensionalized with the wave height, h_o, and pitch, Θ_o in radians, by the maximum waveslope, $2\pi/\lambda\ h_o$. Full lines represent theoretically computed motion amplitudes and experimentally determined motion amplitudes are represented by circled points.

Figures XIII and XIV compare catamaran theory predictions with experimental results. Figures XV and XVI show ALVIN comparisons in Heave and Figures XVII and XVIII show ALVIN comparisons in Pitch. Figure XIX is a comparison of ALVIN with and without heave instrumentation. Figures XX and XXI are comparisons of the two vessels in the recovery position. Figures XXII and XXIII are comparisons of ALVIN alone and in recovery position. Figure XXIV compares the catamaran alone and with ALVIN in recovery position for heave motion.

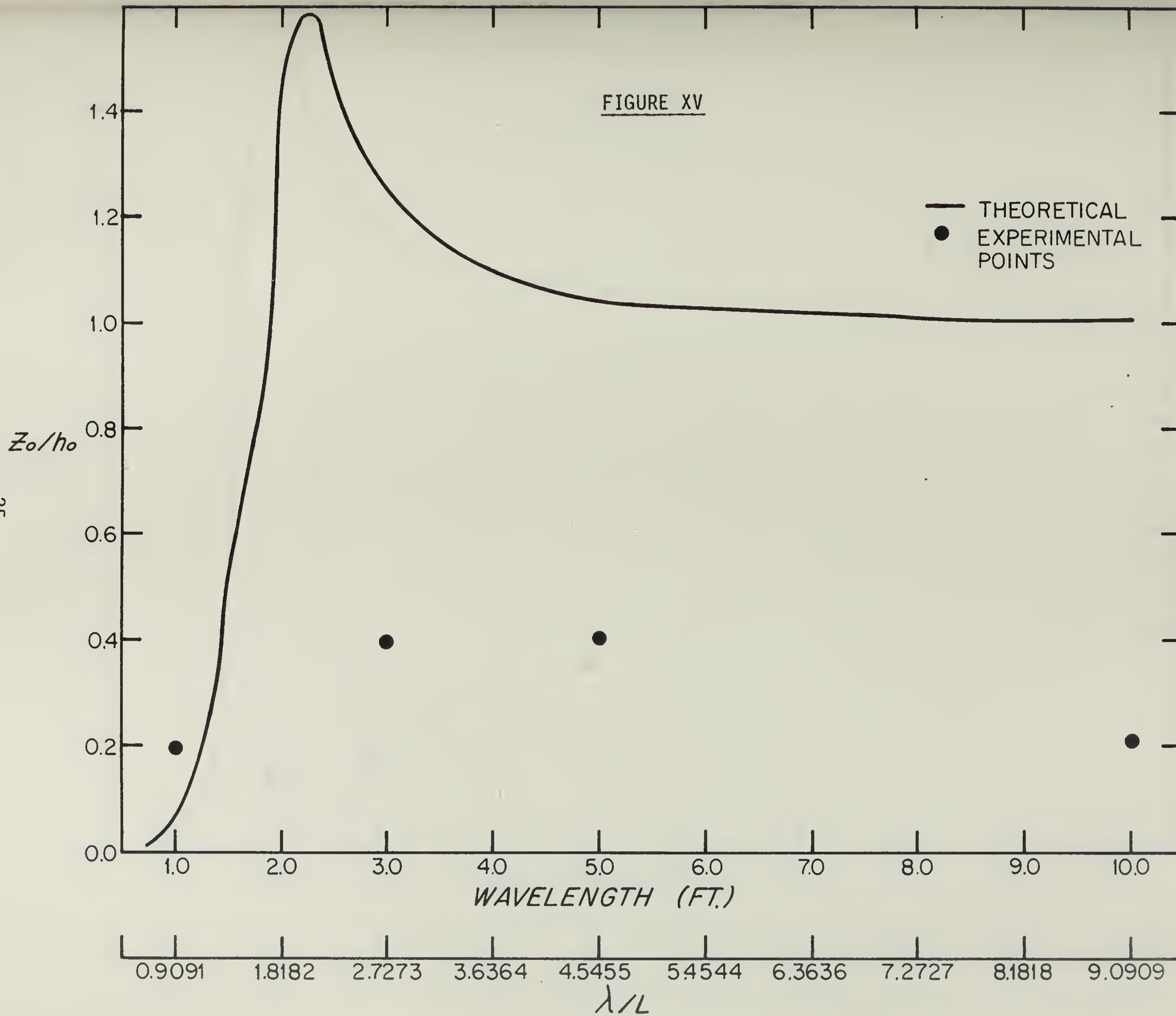
FIGURE XIII



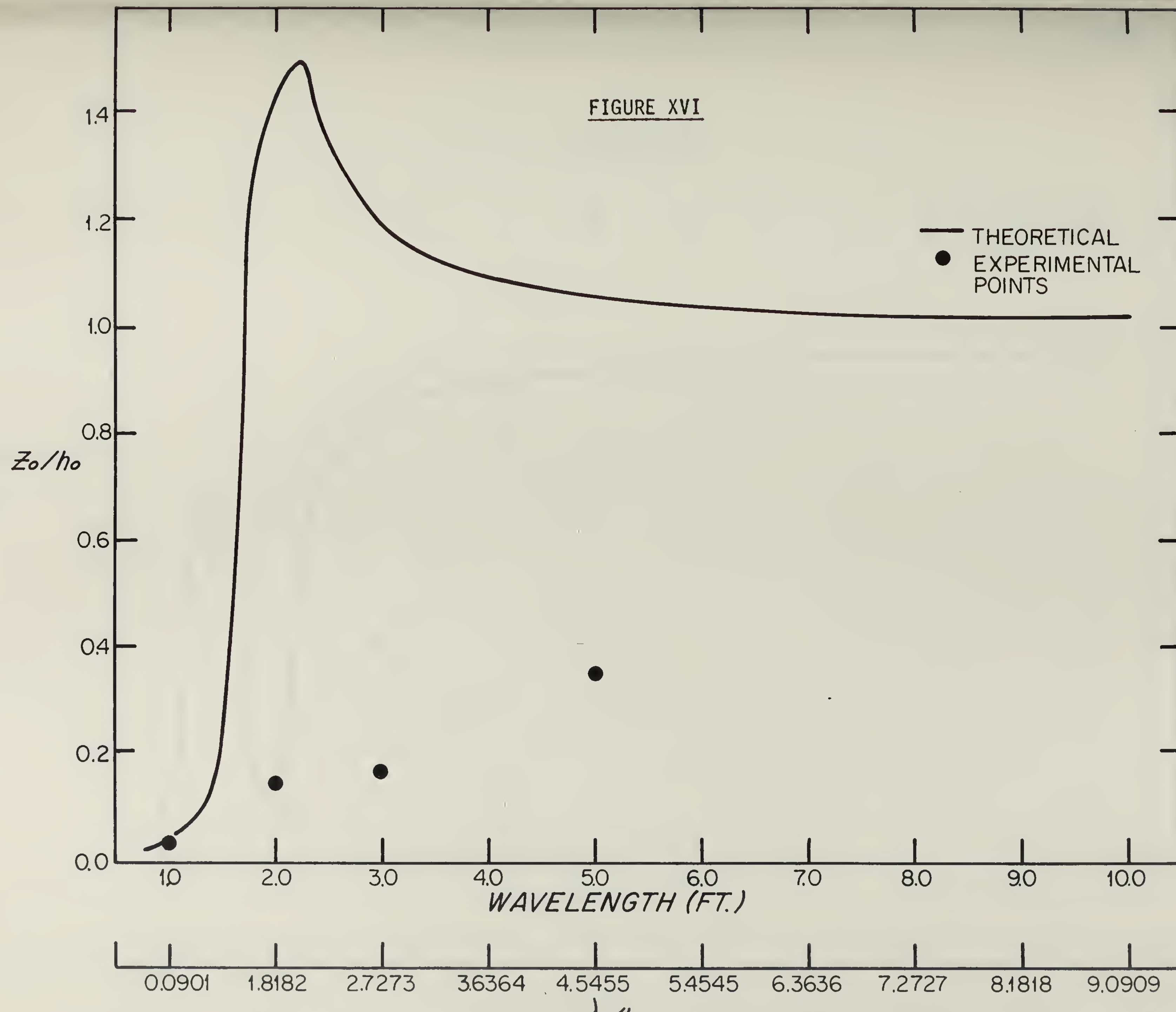
CATAMARAN MODEL THEORETICAL AND EXPERIMENTAL HEAVE AMPLITUDE



CATAMARAN MODEL THEORETICAL AND EXPERIMENTAL PITCH AMPLITUDE



ALVIN MODEL THEORETICAL AND EXPERIMENTAL HEAVE AMPLITUDE - DIRECTLY AHEAD SEAS



ALVIN MODEL THEORETICAL AND EXPERIMENTAL HEAVE AMPLITUDE - DIRECTLY ASTERN SEAS

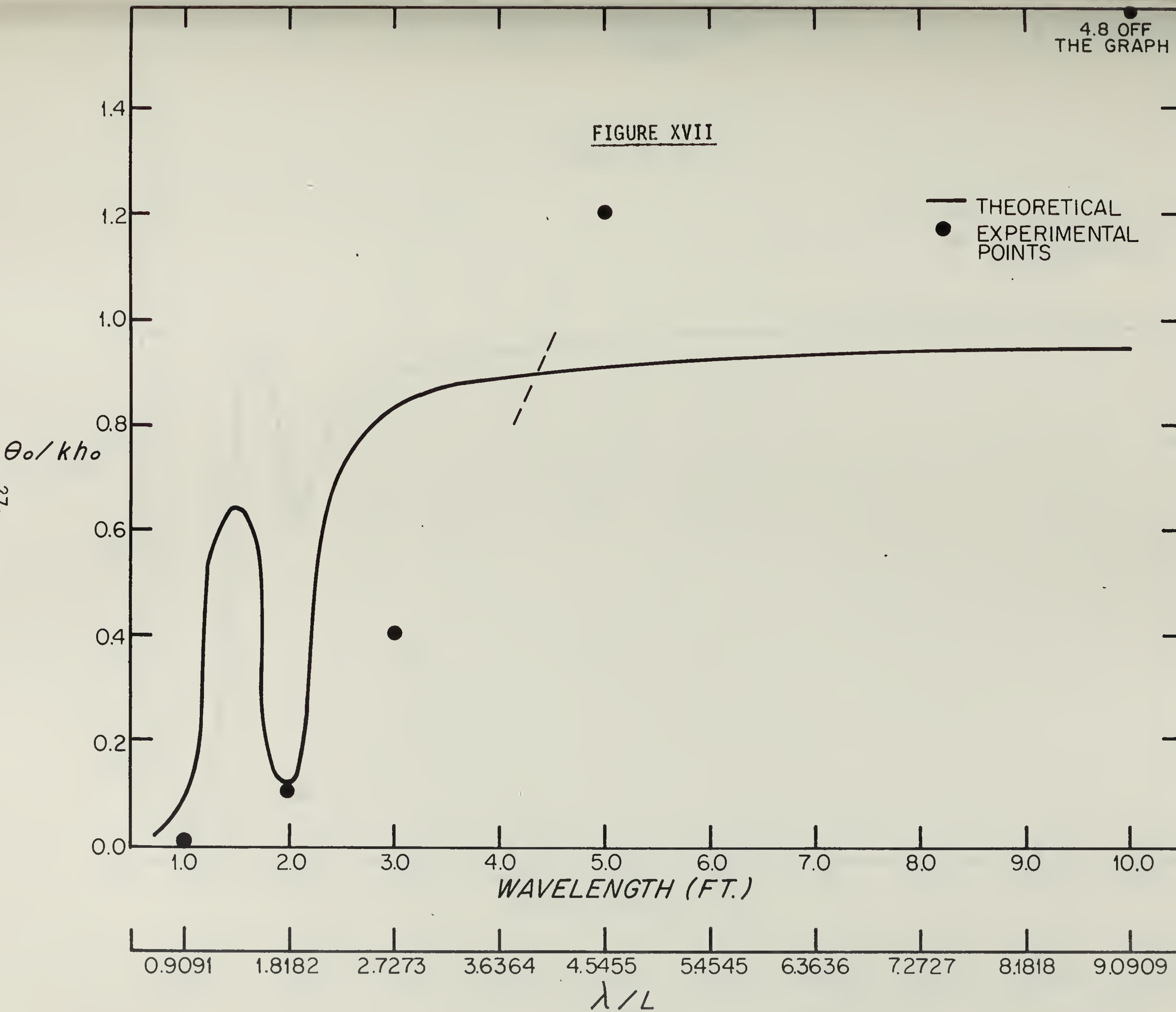
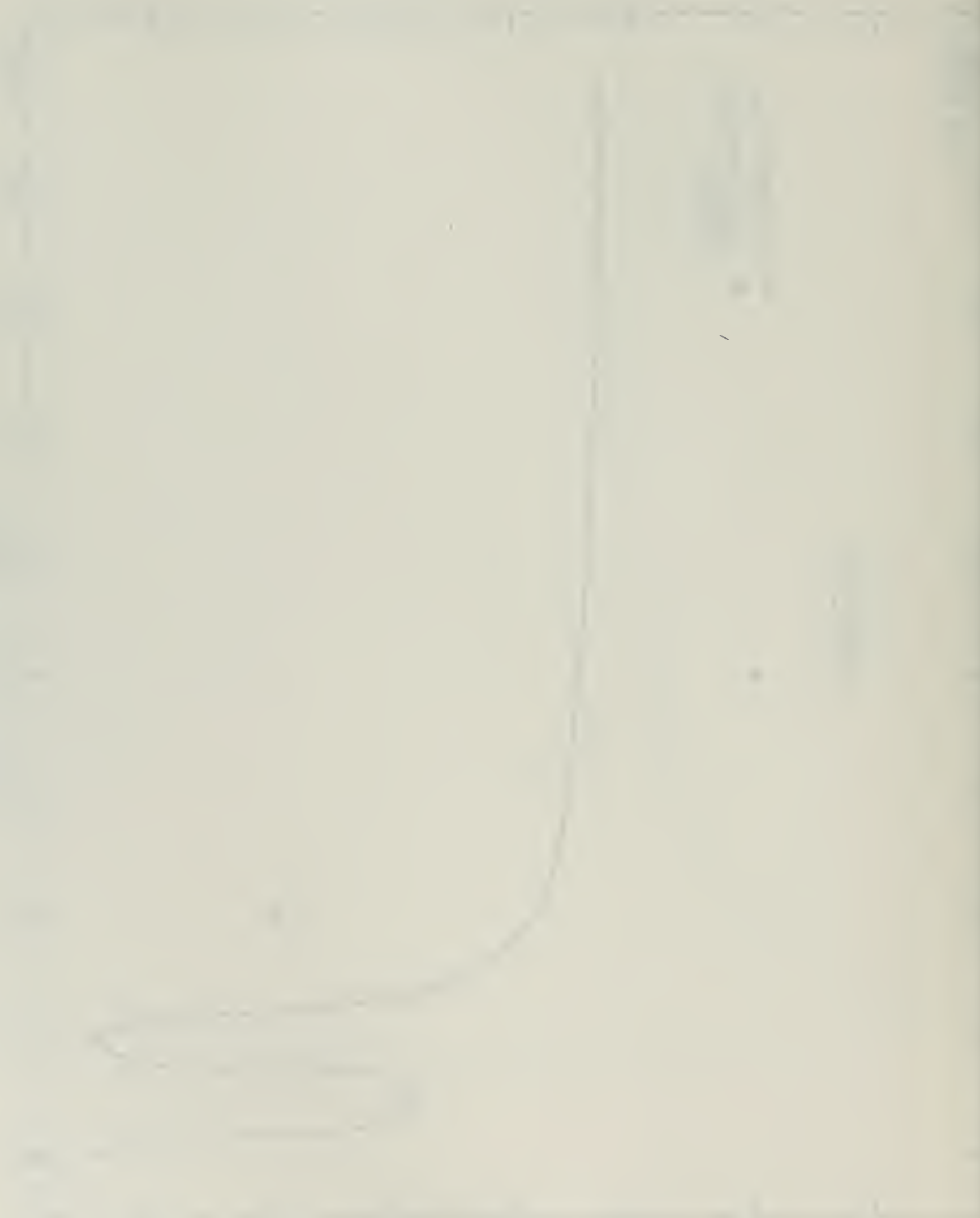
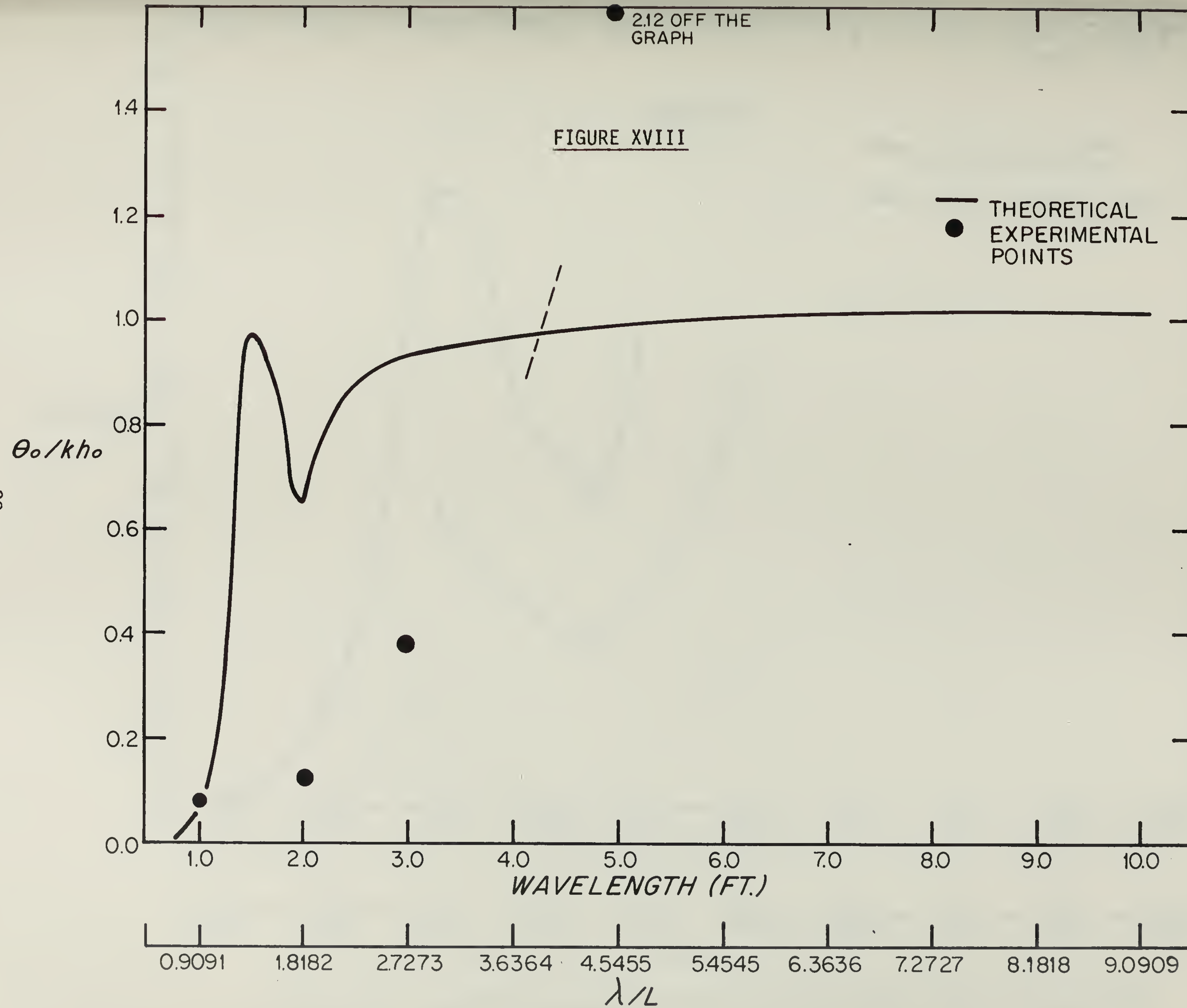


FIGURE XVII

ALVIN MODEL THEORETICAL AND EXPERIMENTAL PITCH AMPLITUDE - DIRECTLY AHEAD SEAS





ALVIN MODEL THEORETICAL AND EXPERIMENTAL PITCH AMPLITUDE - DIRECTLY ASTERN SEAS

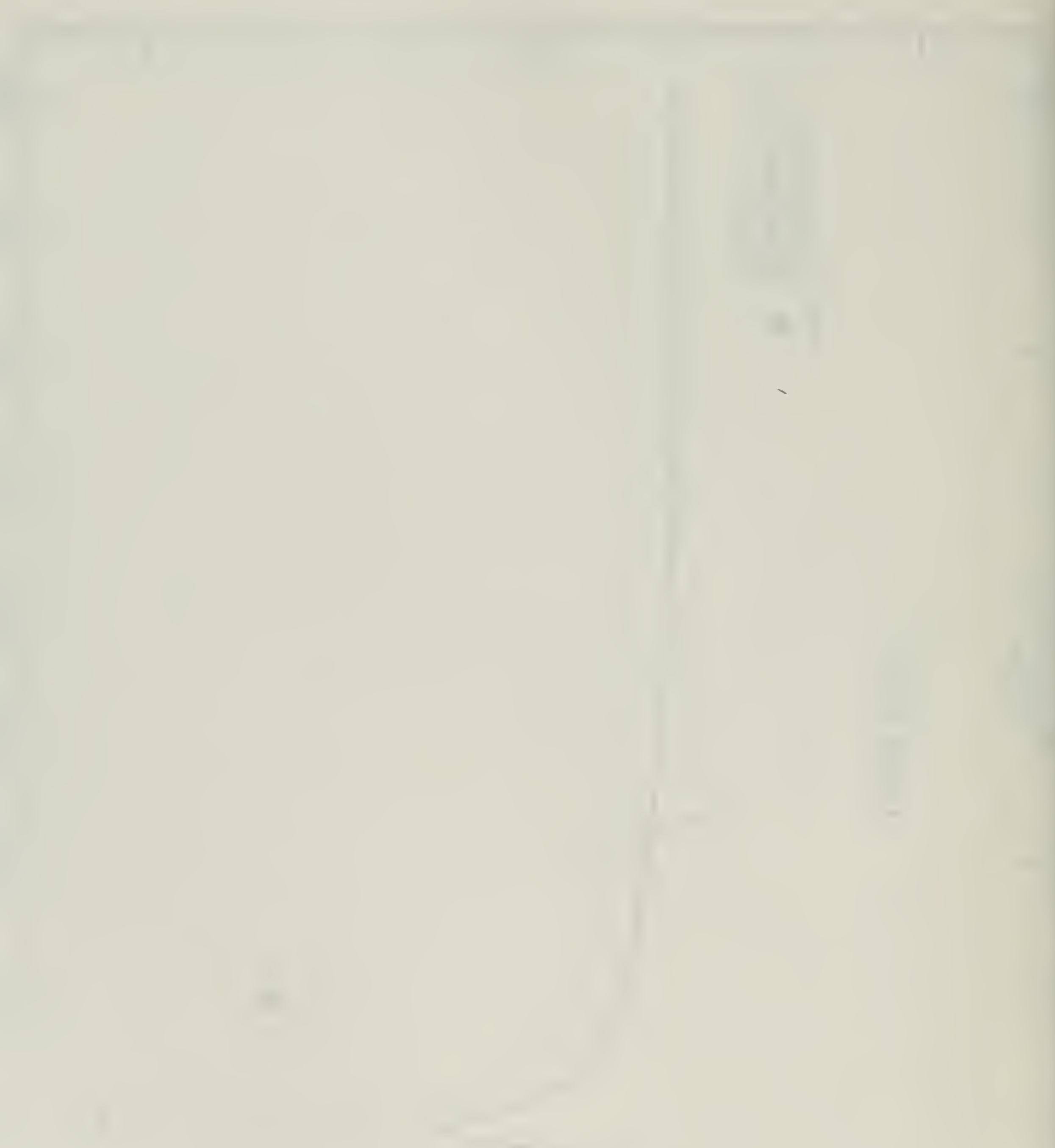
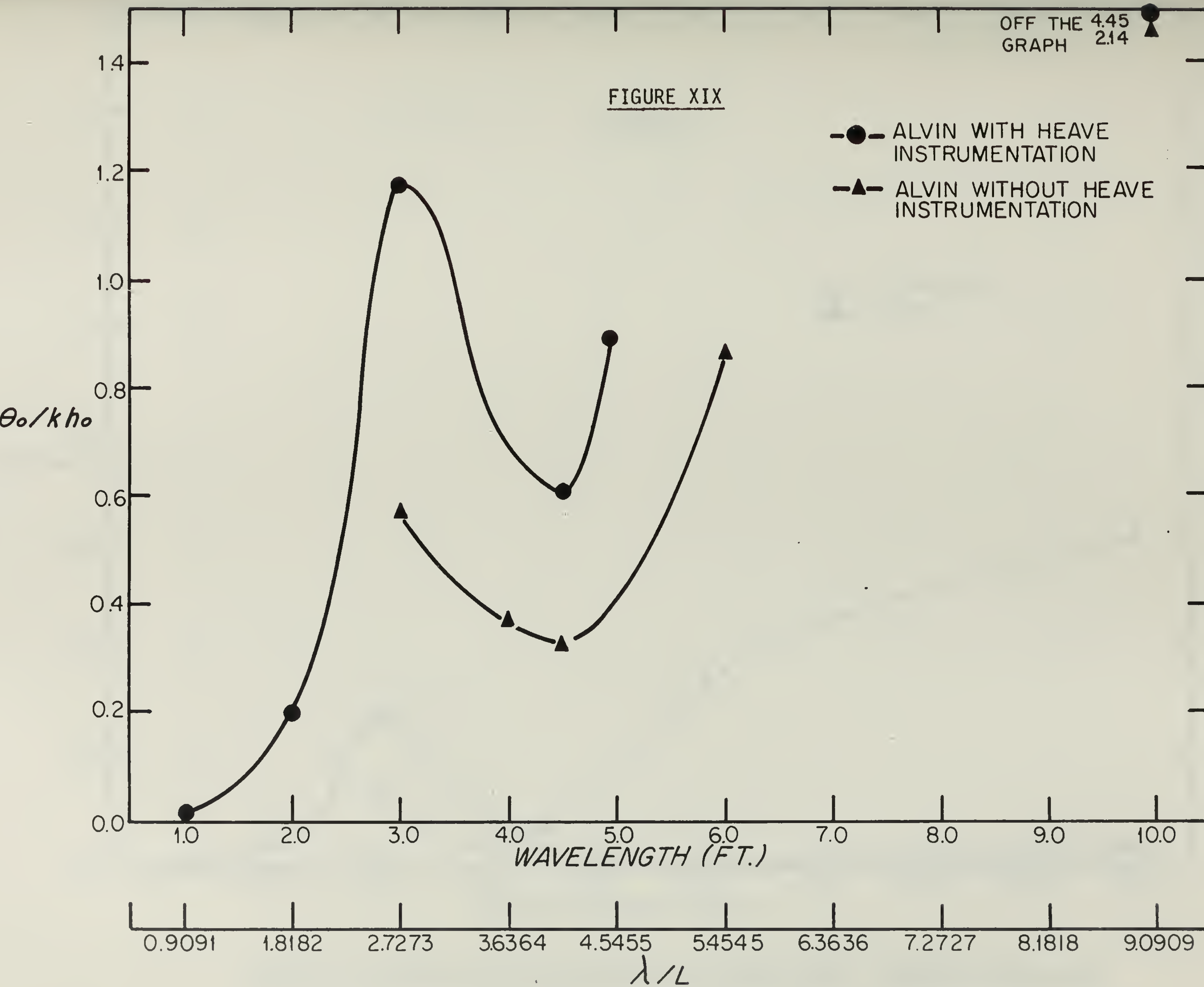
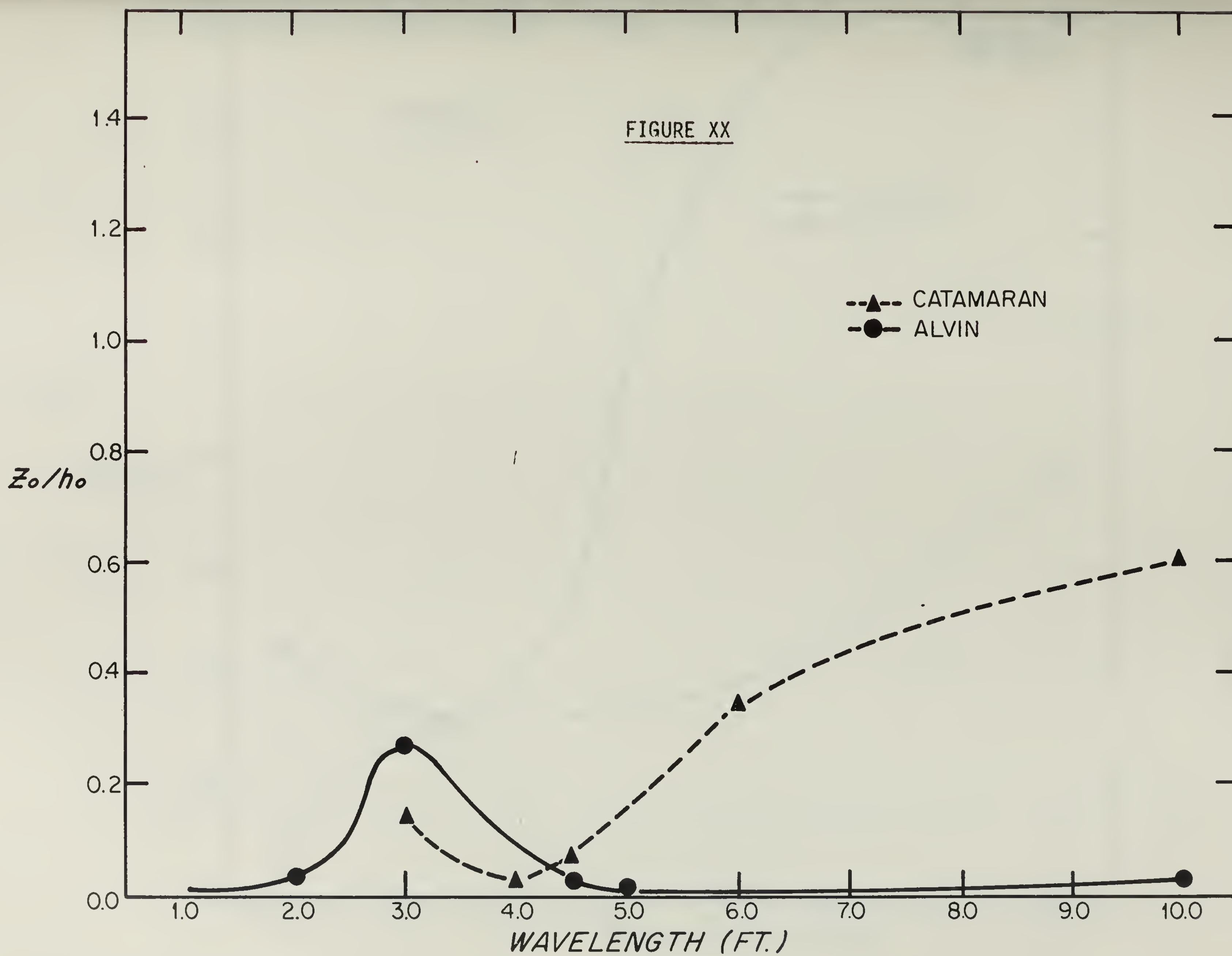


FIGURE XIX



ALVIN MODEL EXPERIMENTAL PITCH AMPLITUDE WITH AND WITHOUT HEAVE INSTRUMENTATION



RECOVERY POSITION, MODEL EXPERIMENTAL HEAVE AMPLITUDE - DIRECTLY AHEAD SEAS

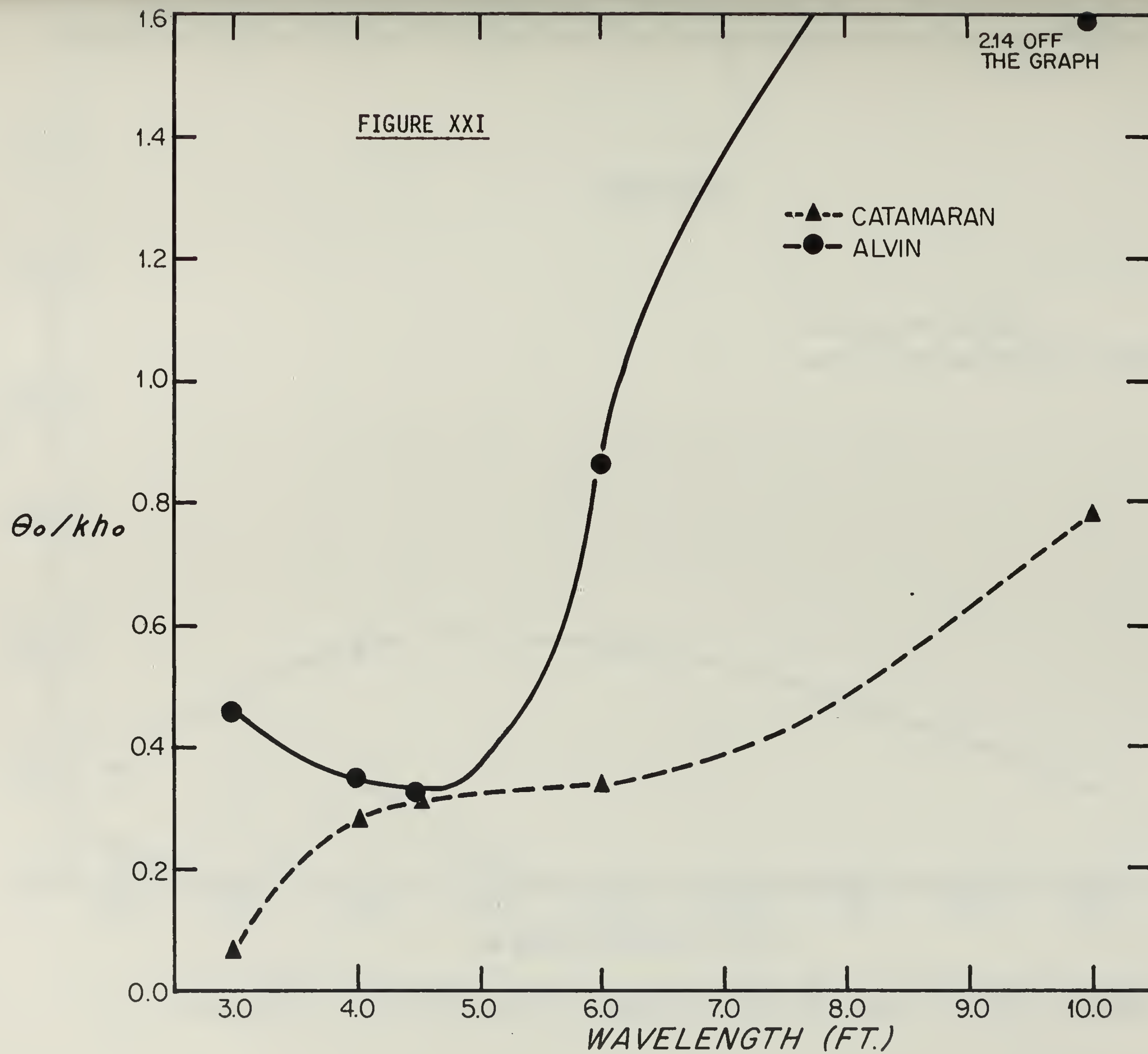
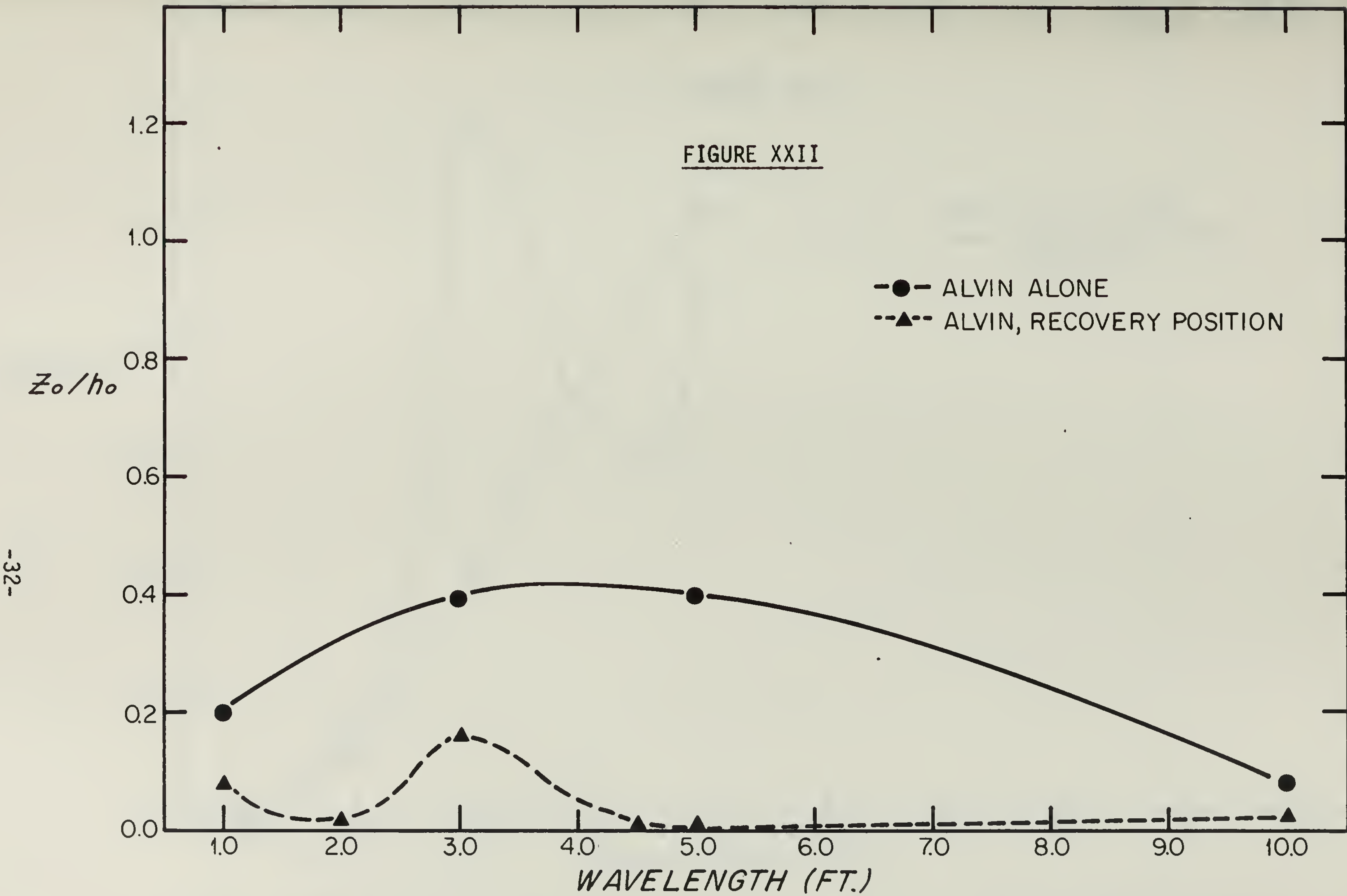


FIGURE XXI

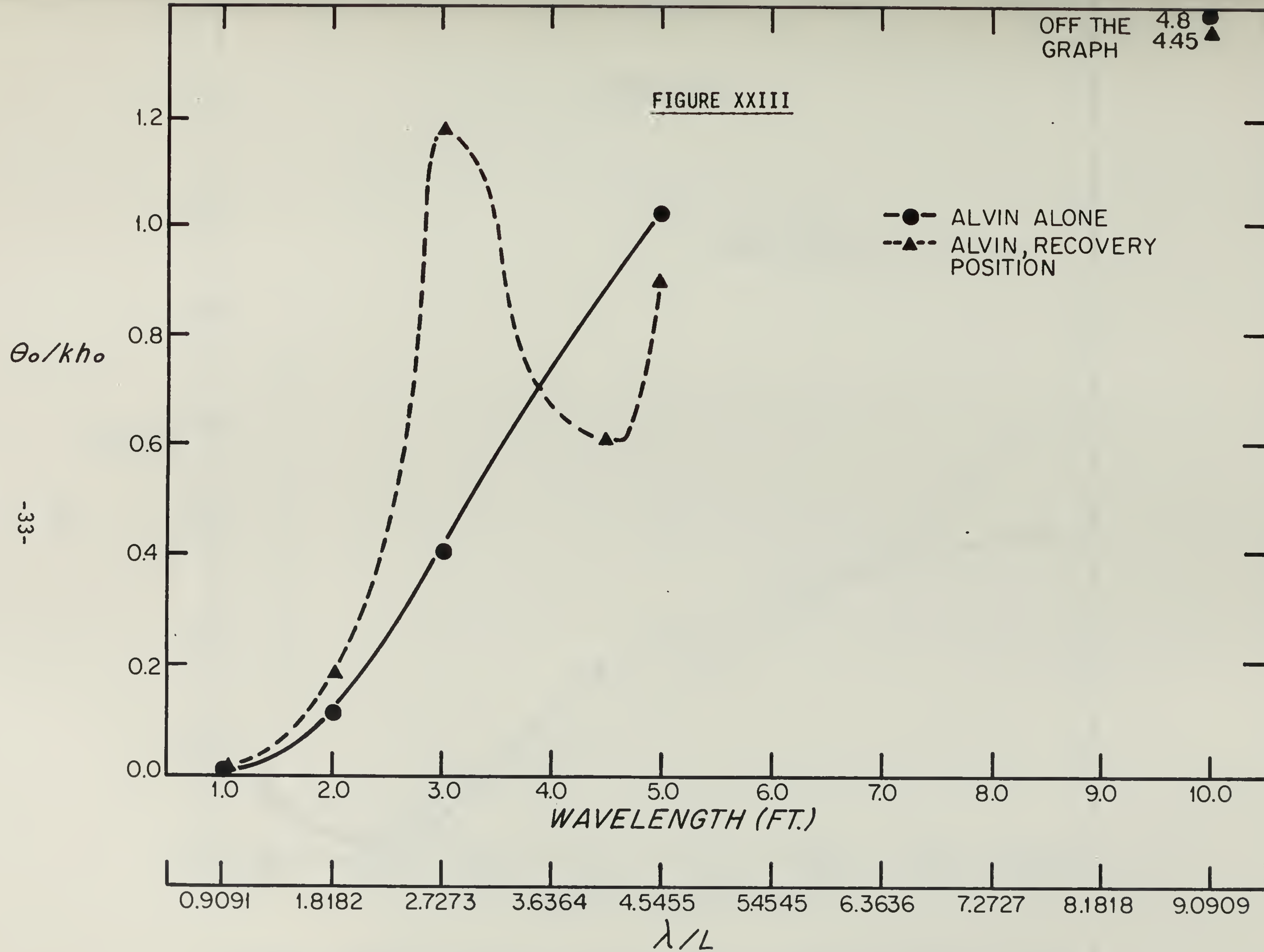
RECOVERY POSITION MODEL EXPERIMENTAL PITCH AMPLITUDE - DIRECTLY AHEAD SEAS

FIGURE XXII



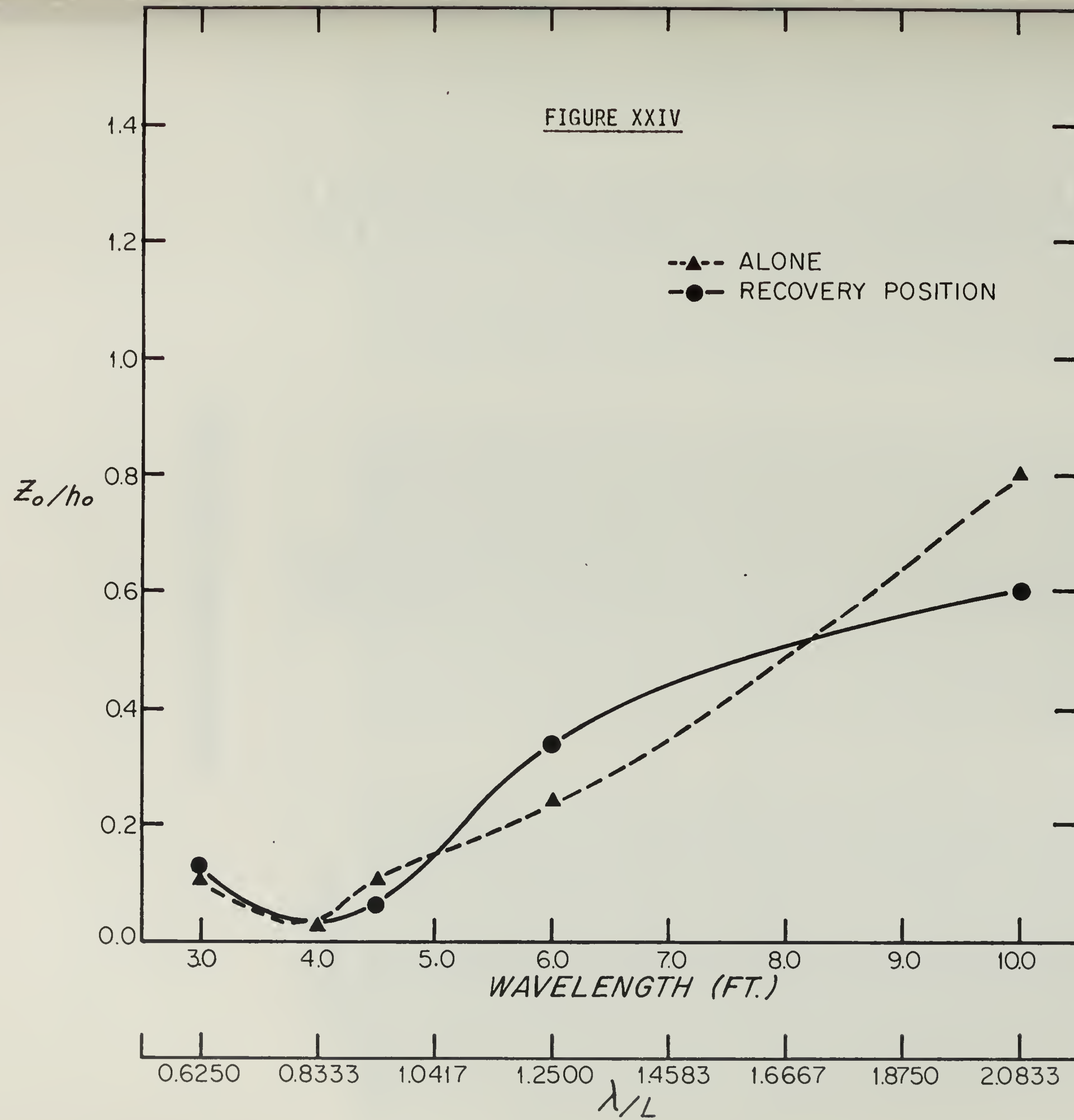
ALVIN MODEL EXPERIMENTAL HEAVE AMPLITUDE ALONE AND IN THE RECOVERY POSITION

FIGURE XXIII



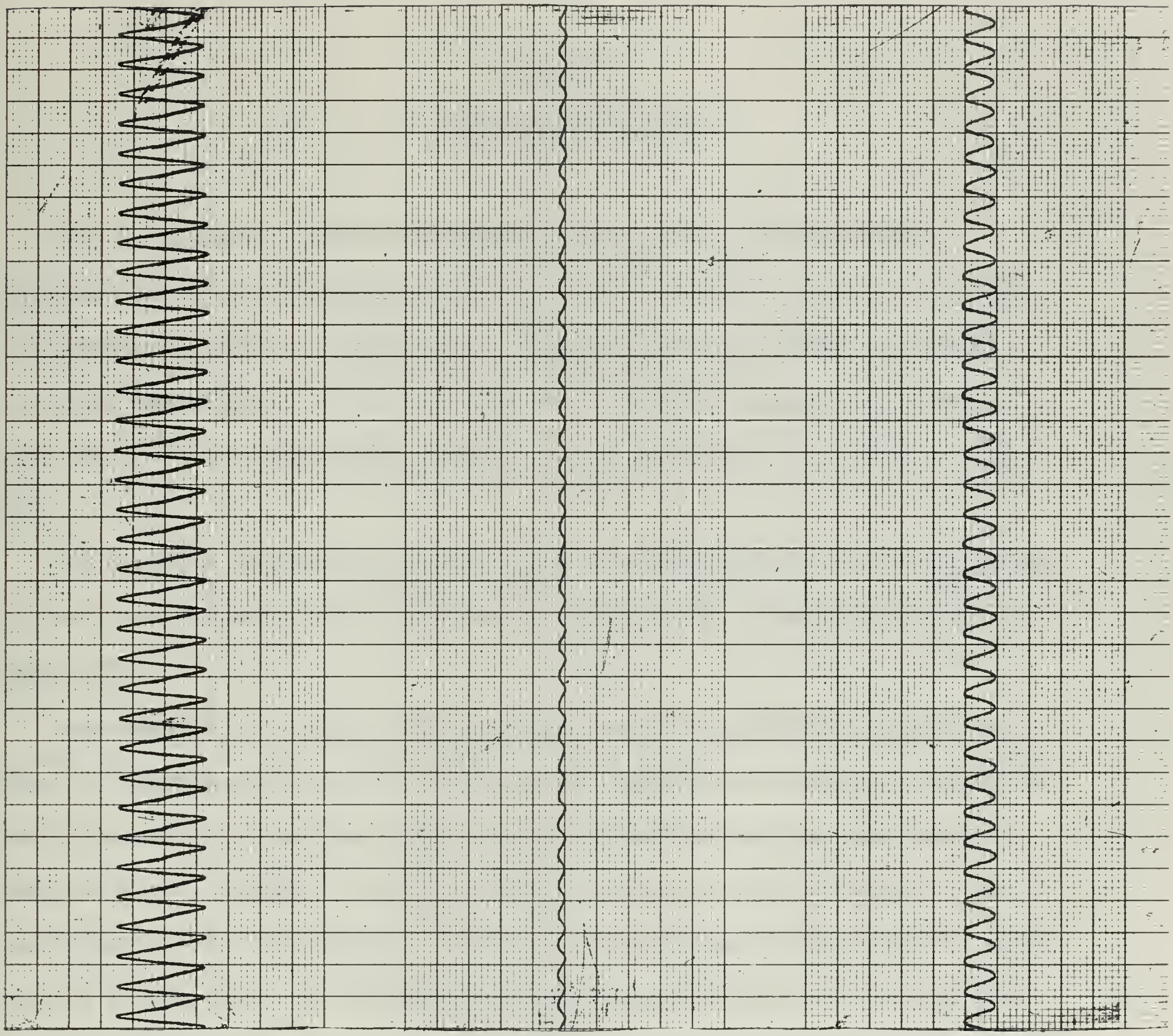
ALVIN MODEL EXPERIMENTAL PITCH AMPLITUDE ALONE AND IN THE RECOVERY POSITION

FIGURE XXIV



CATAMARAN MODEL EXPERIMENTAL HEAVE AMPLITUDE ALONE AND IN THE RECOVERY POSITION

FIGURE XXV



TYPICAL OSCILLOGRAPH RECORDING

CHAPTER V

DISCUSSION OF RESULTS

For the catamaran, after the theoretically computed heaving motion amplitudes had been corrected, the plotted curve correctly predicted the trend of experimental results. While theory predicted somewhat higher at shorter and longer wavelengths, in the range of 0.9 to 1.5 wavelength to shiplength ratio there was reasonably close agreement with experimental results. (Figure XIII).

The curve of corrected theoretical pitching amplitudes correctly predicted the trend but was about 20% higher than experimentally determined results. (Figure XIV).

Instrumenting the small ALVIN model was extremely difficult because the weight of instrumentation was of the order of magnitude of weight of the model. A hollow heave rod of tubular aluminum was substituted for the solid square steel heave rod. However, during the model testing for motion response, the light weight of the instrumented ALVIN was not sufficient to overcome the small friction in the guides of the heave rod and linearsyn core rod. For many runs no vertical oscillation was recorded at all. The runs where heave motion was recorded showed intermediate binding so that all experimental heave data of ALVIN was considered questionable.

Because of the undesired restraint on vertical motion, the model responded to the wave action with amplified pitch motion. An example of this is shown in Figure XIX, which compares the pitching motion with and without the linearsyn

rod. This proves that pitching motion was artificially increased due to this unwanted restraint. Another piece of evidence is the fact that at 5.0 ft. wavelengths and 10.0 ft. wavelengths pitch exceeded by a factor of 2-5 the maximum waveslope. At pitch angles about equal to 5 degrees bow up the center of buoyancy shift was great enough to cause an instability in the model and it would flip stern down. For this reason, the maximum wave amplitude that could be used with ALVIN was 0.75 in. crest to trough.

Comparisons with theoretically computed heave and pitch motions amplitudes were nevertheless made, albeit somewhat questionable. Theoretical results were higher for both directly ahead and astern seas. Also the curve of theoretical results of heaving amplitudes predicted a resonance at the 2.25 ft. wavelength that was not verified by the experimental data. (Figures XV and XVI). For ALVIN pitching motions the experimentally determined results crossed the theoretical curve at about 4.0 ft. wavelength in both directly ahead and astern seas where the restraint in vertical motion caused greater pitching motion of the model. (Figures XVII and XVIII).

The recovery position motion data shows that for heaving amplitudes the two vessels first follow the same trend with ALVIN heaving slightly more than the catamaran at wavelengths shorter than the catamaran length then about the same at a wavelength 90% of the catamaran length. Then the curves of heaving amplitude diverge with the catamaran heaving amplitude greater. (Figure XX). This is contrary to the author's observations during the runs, when it was directly observed at the 4.5 ft. wavelength the ships seemed to move in perfect synchronism and exhibited similar, though less perfect, synchronism as the wavelength increased. The discrepancy between measured results and observation may

be caused by binding of the heave instrumentation on the ALVIN model.

For the recovery position pitching motion, the rapid divergence of ALVIN at longer wavelengths is felt to be, again, due to the restraint in heave. (Figure XXI).

ALVIN's effect on catamaran heaving motion appears to be slight and highly frequency (wavelength) dependent. (Figure XXII).

ALVIN's heaving motion amplitude appears to be significantly damped (Figure XXIII).

ALVIN's pitching motion, however, is amplified at the shorter wavelengths with a resonance at a wavelength 62% of the catamaran, and damped slightly at a wavelength 90% of the catamaran length. (Figure XIV). This is, again, inconclusive because of the ALVIN model instrumentation.

Reasons for Discrepancies

The experimental methods and the current status of theoretical knowledge possess many sources of errors. To provide a partial explanation of the differences in this investigation between theory and experiment and the differences between the models, these discrepancies are discussed.

For the experimental work, the following sources of discrepancies exist:

a) Wave height measurement is one of the greatest sources of errors in tow tank work[7]. The potentiometer settings for wave-heights were determined with no models in the tank to eliminate the model effect on the wave height measured. However, as the potentiometer settings were quite delicate, this may have led to errors.

b) Wall effects, or reflection from the walls back onto the model of waves generated by the model motion at zero forward speed and at small wavelengths significantly affected the results[2,7].

c) Undesired instrument effects on the model may have affected the results, as was previously discussed for the ALVIN model.

d) Instrument accuracy was about ±2.5%.

e) Extraction of recorded data on oscillograph recorder tapes may have introduced errors.

f) During the 1.0 ft. wavelength generation, the hydraulic ram pushing the paddle was observed to loosen on its foundation and a modulated wave record resulted. This may have affected other wavelengths, but oscillograph records appeared to be regular.

For the theoretical computations, the following assumptions limited the applicability of the theory to ALVIN and the catamaran:

a) linearized theory assumes ship section lines vertical at the waterline. Neither of the models have vertical sides, especially in the case of ALVIN.

b) the computation of damping in linear theory is by accounting for the energy dissipated in gravity waves generated when the ship oscillates. Frictional, separation, and circulation phenomena are assumed to be negligible, which is generally valid for surface ships[5]. This assumption is erroneous for ALVIN where the above phenomena are a considerable influence.

c) linear theory assumes small motions and that coefficients of motion are constant throughout the whole cycle of motion. This is not true for larger motions. The restoring force coefficients are correct only for vertical sides at the waterline. For the ALVIN model with a decreasing and increasing waterplane area as the model oscillates up and down, this is certainly not true.

d) end effects or three-dimensional effects are responsible for large discrepancies when large section areas are present at the ends of the model. The sectional area curve must go "gracefully" to zero at the bow and stern in order for the force contributions of these sections to zero. This does not affect the heave coefficients seriously but the ends of the ship have a double effect on pitching and therefore significant errors may result in pitching motions[5]. This is serious inadequacy in applicability of the theory to ALVIN.

e) linear strip theory has a basic assumption that beam and draft are small compared to length and uses a basically two-dimensional approach[5]. This is another serious inadequacy in the applicability of the theory to ALVIN, which has a length to beam ratio of 2.6 and a length to draft ratio of 3.1.

CHAPTER VI

CONCLUSIONS

The conclusions from the preceding chapters are summarized.

1. The catamaran corrected theoretical results, in spite of discrepancies noted previously, predicts and agrees reasonably well with the experimental results.
2. The Korvin-Krovkorsky linear theory, with Grim's added mass and damping, applicability to ALVIN is questionable but this conclusion cannot be substantiated because of inaccurate experimental data.
3. Because of the inapplicability of theory and the questionable experimental data, a valid comparison could not be made between ALVIN theoretical predictions and experimental results.
4. ALVIN and the catamaran respond in synchronous motion at wavelengths about equal to the length of the catamaran, but this conclusion is questionable because of ALVIN experimental data.
5. ALVIN heaving motion is appreciably damped in the recovery position between the catamaran hulls, but this conclusion is questionable because of ALVIN experimental data.
6. The catamaran heaving motion is not significantly affected by ALVIN in the recovery position.

CHAPTER VII

RECOMMENDATIONS

Much research remains to be done in the design of surface support vessels for lauching and recovery of deep submersibles in the open ocean. Therefore it seems important that further theoretical and experimental work be undertaken in this important part of the "Deep Submergence Vehicle System."

Recommendations arising from this investigation are that;

1) the theory be modified to extend its applicability to deep submersibles in surfaced condition similar to the hull form of ALVIN. There exists in the literature the more general analysis of Porter[18] and Bermejo[18] that accounts for section shape in more detail.

2) the comparisons attempted in this investigation be repeated with special attention given to devising better heave instrumentation for ALVIN or larger scale models be used.

3) this investigation should be extended by experimentally determining phase angles of motion and comparing them with the theoretical computed phase angles (that were not used in this investigation).

4) an experimental investigation be made using different support vessel hull forms to determine the optimum hull form for open ocean.

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APPENDIX

APPENDIX A

NOMENCLATURE

a = coefficient of equation of motion

A = coefficient of equation of motion

b = coefficient of equation of motion

B = coefficient of equation of motion

c = coefficient of equation of motion

C = coefficient of equation of motion

d = coefficient of equation of motion

D = coefficient of equation of motion

e = coefficient of equation of motion

E = coefficient of equation of motion

F = total vertical (heaving) force

F_o = amplitude of time-varying heaving force

$\overline{F}$ = complex vertical (heaving) force

g = gravitational acceleration

g = coefficient of equation of motion

G = coefficient of equation of motion

h_o = amplitude of sinusoidal wave (half-wave height)

K = maximum wave slope, $(2\pi/\lambda\ h_o)$

K_g = longitudinal radius of gyration

L = length of ship or model

m = mass of ship or model

M = total pitching moment

M_o = amplitude of time-varying pitching moment

$\overline{M}$ = complex pitching moment

$N(\xi)$ = sectional damping coefficient

t = time

v = speed of ship or model

z = heaving motion of center of gravity of ship or model

$\dot{z}$ = heaving velocity of center of gravity of ship or model

$\ddot{z}$ = heaving acceleration of center of gravity of ship or model

z_o = amplitude of heaving motion

$\overline{z}$ = complex heaving motion

Greek Letters

δ = theoretically computed heaving phase angle

Δ = displacement of ship or model

ε = theoretically computed pitching phase angle

θ = pitching displacement

θ = pitching velocity

$\ddot{\theta}$ = pitching accelerations

Θ_o = amplitude of pitching motion

$\overline{\Theta}$ = complex pitching motion

λ = wavelength

ρ = water density

σ = phase angle of heaving force

τ = phase angle of pitching moment

ω_e = frequency of encounter

APPENDIX B

ANALYTICAL DETAILS OF THE LINEAR THEORY OF SHIP MOTIONS

In order to achieve completeness and simultaneously provide easy reference, the fundamental analytical expressions of the Korvin-Kroukovsky method, as utilized in the computer program, are summarized in this Appendix. Following the nomenclature and definitions adopted in (8), the coupled set of linear differential equations describing the two-degree-of-freedom ship system, takes the form,

$$
\begin{aligned}
a\ddot{z} + b\dot{z} + cz + d\ddot{\Theta} + e\Theta + g\dot{\Theta} &= \overline{F} \exp (i\omega_e t) \\
A\ddot{\Theta} + B\dot{\Theta} + C\Theta + D\ddot{z} + E\dot{z} + Gz &= \overline{M} \exp (i\omega_e t)
\end{aligned}
\qquad (1)
$$

The above equations result from equilibrium considerations of the hydrodynamic forces and moments called into play by the ship's oscillations in the plane of symmetry, when meeting head or astern regular waves. For this reason the analysis ignores steady, continuously acting forces due to buoyancy, gravity and suction pressures. Following the principles of classical dynamics, these forces and moments are obtained by applying Newton's Second Law of Motion to both translatory and rotational displacements of the body's center of gravity.

The wave induced excitation force and moment may be thought of as being imposed on a fully restrained ship and appear on the RHS of the set (1). They have the useful property that they are functions of the wave elevation and its two first time derivatives, thereby allowing ease in algebraic manipulation[7]. They are defined in complex notation as

$$
\begin{aligned}
\overline{F} \exp (i\omega_e t) &= F_o \exp (-i\sigma) \exp (i\omega_e t) = F_o \exp [i(\omega_e t-\sigma)] \\
\overline{M} \exp (i\omega_e t) &= M_o \exp (-i\tau) \exp (i\omega_e t) = M_o \exp [i(\omega_e t-\tau)]
\end{aligned}
\qquad (2)
$$

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

The differential exciting force acting on a control section distant ξ from the origin of the moving coordinate system (ship's C.G.), has been given in (8) in the simplified form,

$$\frac{dF}{dx} = \frac{dF_1}{dx} \cos \omega_e t + \frac{dF_2}{dx} \sin \omega_e t$$

$$= [\{\phi_1 \sin \frac{2\pi\xi}{\lambda} + \phi_2 \frac{2\pi hc_w}{\lambda} \cos \frac{2\pi\xi}{\lambda}\} \exp (- \frac{2\pi y}{\lambda}] \cos \omega_e t$$

$$+ [\{\phi_1 \cos \frac{2\pi\xi}{\lambda} - \phi_2 \frac{2\pi hc_w}{\lambda} \sin \frac{2\pi\xi}{\lambda}\} \exp (- \frac{2\pi y}{\lambda})] \sin \omega_e t \tag{3}$$

where,

$$\phi_1 = h\rho g\ B* - \frac{4\pi^2 hc_w^{\ 2}}{\lambda^2} (\rho\ Sk_2k_4)$$

and,

$$\phi_2 = N(\xi) - V \frac{d(\rho\ Sk_2k_4)}{d\xi}$$

while the differential exciting moment of this force about the C.G. is given by $\frac{dF}{dx}\ d\xi$. Integration of the above two quantities over the ship length results in the values of the total time-varying exciting force and moment, which are considered as the real parts of the expressions (2). Thus,

$$F = F_1 \cos \omega_e t + F_2 \sin \omega_e t \qquad M = M_1 \cos \omega_e t + M_2 \sin \omega_e t$$

$$= \sqrt{F_1^{\ 2} + F_2^{\ 2}} \cos[\omega_e t - \arctan \frac{F_2}{F_1}] \quad \text{and} \quad = \sqrt{M_1^{\ 2} + M_2^{\ 2}} \cos[\omega_e t - \arctan \frac{M_2}{M_1}]$$

$$= F_o \cos(\omega_e t - \sigma) \qquad = M_o \cos(\omega_e t - \tau) \tag{4}$$

The analysis of the forces and moments which correspond to the ship's free oscillations in calm water yields terms which appear on the LHS of the set (1) and are proportional to the instantaneous heaving and pitching displacement, velocities and accelerations. All twelve coefficients of the above terms are independent of the speed per se and the body's space orientation, but depend on the frequency of encounter, with the exception of c and G. The final expressions for the coefficients of the equation of motion used in the machine computations are listed below:

$$
\begin{aligned}
a &= m + \rho \int (Sk_2 k_4)\, d\xi \\
b &= \int N(\xi)\, d\xi \\
c &= \rho\, g \int B^*\, d\xi \\
d &= \rho \int (Sk_2 k_4)\, \xi\, d\xi \\
e &= \int N(\xi)\, \xi\, d\xi - 2V \rho \int (Sk_2 k_4)\, d\xi - V \rho \int d\, (Sk\, k_4)/d\xi\, \xi\, d\xi \\
g &= \rho\, g \int B^*\, \xi\, d\xi - V \int N(\xi)\, d\xi \qquad\qquad (5) \\
A &= J + \rho \int (Sk_2 k_4)\, \xi^2\, d\xi \\
B &= \int N(\xi)\, \xi^2\, d\xi - 2V \rho \int (Sk_2 k_4)\, \xi\, d\xi - V \rho \int d\, (Sk_2 k_4)/d\xi\, \xi^2\, d\xi \\
C &= \rho\, g \int B^*\, \xi^2\, d\xi - V \int N(\xi)\, \xi\, d\xi + v^2 \rho \int d\, (Sk_2 k_4)/d\xi\, \xi\, d\xi \\
D &= \rho \int (Sk_2 k_4)\, \xi\, d\xi \\
E &= \int N(\xi)\, \xi\, d\xi - V \rho \int d\, (Sk_2 k_4)/d\xi\, \xi\, d\xi \\
G &= \rho\, g \int B^*\, \xi\, d\xi
\end{aligned}
$$

Assuming now that sufficient time has elapsed for any transient disturbances to be damped out, we seek particular solutions of the nonhomogeneous set (1), which correspond to the steady-state responses of the system. Since the

forcing functions are sinusoidal and the system is linear and time-invariant, we expect that any response will also be sinusoidal of the same frequency as the excitation and with generally different amplitude and phase. We therefore assume solutions of the form,

$$z(t) = z = \bar{z} \exp(i\omega_e t$$

$$\text{and} \quad \Theta(t) = \Theta = \bar{\Theta} \exp(i\omega_e t) \qquad (6)$$

with the arbitrary definitions,

$$\bar{z} = z_o \exp(-i\delta)$$

$$\text{and} \quad \bar{\Theta} = \Theta_o \exp(-i\varepsilon) \qquad (7)$$

Upon substitution in the original equations (1), a conscientious algebraic manipulation yields the following expressions for the "complex" heaving and pitching amplitudes,

$$\bar{z} = \frac{\bar{F}S-\bar{M}Q}{PS-QR} \quad \text{and} \quad \bar{\Theta} = \frac{\bar{M}P-\bar{F}R}{PS-QR} \qquad (8)$$

where,

$$\bar{F} = F_o(\cos\sigma - i\sin\sigma)$$

$$\bar{M} = M_o(\cos\tau - i\sin\tau)$$

$$P = (c-a\omega^2_e) + i\, b\, \omega_e$$

$$S = (C-A\omega^2_e) + i\, B\, \omega_e \qquad (9)$$

$$Q = (g-d\omega^2_e) + i\, e\, \omega_e$$

$$R = (G-D\omega^2_e) + i\, E\, \omega_e$$

It follows from (8) and (9) that the "complex" amplitudes may be expressed as,

$$\bar{z} = z_1 - i\,z_2 = \sqrt{z_1^{\,2}+z_2^{\,2}}\ \exp[-i\ \arctan \frac{z_2}{z_1}] \tag{10}$$

$$\text{and}\quad \bar{\Theta} = \Theta_1 - i\,\Theta_2 = \sqrt{\Theta_1^{\,2}+\Theta_2^{\,2}}\ \exp[-i\ \arctan \frac{\Theta_2}{\Theta_1}]$$

Considering the real parts of (6), we finally obtain,

$$\begin{aligned} z &= R_e\ \bar{z}\ \exp(i\omega_e t) \\ &= \text{Re}\ \sqrt{z_1^{\,2}+z_2^{\,2}}\ \exp[i(\omega_e t - \arctan \frac{z_2}{z_1}] \\ &= z_o\ \cos(\omega_e t - \delta) \end{aligned} \tag{11}$$

$$\begin{aligned} \text{and}\quad \Theta &= R_e\ \bar{\Theta}\ \exp(i\omega_e t) \\ &= \text{Re}\ \sqrt{\Theta_1^{\,2}+\Theta_2^{\,2}}\ \exp[i(\omega_e t - \arctan \frac{\Theta_2}{\Theta_1}] \\ &= \Theta_o\ \cos(\omega_e t - \varepsilon) \end{aligned} \tag{12}$$

APPENDIX C

DESCRIPTION OF COMPUTER PROGRAM

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NOMENCLATURE OF COMPUTER PROGRAMS

ABAR(I)	see subroutine ADMAB
ADDA(I)	see subroutine COEFF
ALPHA	phase lag of shearing force
AVETHE	average pitch amplitude
BEEB(I)	see subroutine COEFF
BETA	phase lag of bending moment
BMIMAG	sine term of bending moment
BMNULL	bending moment amplitude
BMREAL	cosine term of bending moment
BPL	ship (model) length between perpendiculars
BSTAR(I)	full beam (breadth) of ship (model) station at DWL
CGGC(I)	see subroutine COEFF
CTFST	see subroutine BENDSH
CW	wave celerity
CXFST	cosine term of exciting force
DELTA	phase lag of heaving motion
DELV	increment of ship or model speed
DELWL	increment of wavelength
DISPL	ship (model) displacement
DIX(I)	$d(Sk_2k_4)/d\xi$
DMASS(I)	station mass
DRAFT(I)	station depth (draft)
DWEIGH(I)	station weight
EMNULL	pitching moment amplitude

ENOX(I)	station damping coefficient
EPSIL	phase lag of pitching motion
FNULL	heaving force amplitude
FROUDE	Froude number
GAMMA	specific weight of water
GRAV	gravitational acceleration
H	interval of Simpson's integration
I	program variable
INCRES	see subroutine BENDSH
KRIT	see subroutine BENDSH
M	no. of ship or model stations
MAXKRI	see subroutine BENDSH
MINKRI	see subroutine BENDSH
N	highest station number
OMEGA	absolute wave frequency
OMEGAE	frequency of encounter
PI	$\pi = 3.1415926$
QUANT(I)	Sk_2k_4
RO	density of water
SECOE(I)	section area coefficient
SHIMAG	sine term of shearing force
SHNULL	shearing force amplitude
SHREAL	cosine term of shearing force
SIGMA	phase lag of heaving force
SKLAM	see subroutine EXCITE and BENDSH

STFST	see subroutine BENDSH
SXFST	sine term of heaving force
SYMPS	area under any curve (see subroutine SIMPS)
TAU	phase lag of pitching moment
TI(I)	see subroutine MOTION
TIMAG	sine term of pitching motion
TMASS	total mass of ship or model
TNULL	amplitude of pitching motion
TR(I)	see subroutine MOTION
TREAL	cosine term of pitching motion
UR(I)	see subroutine MOTION
UI(I)	see subroutine MOTION
V	ship or model speed
VMAX	maximum speed of ship or model
VMIN	minimum speed of ship or model
WA	wave amplitude
WAVEN	wave number
WL	wavelength
XI(I)	longitudinal coordinate of moving (ship) system
Y	see subroutine SIMPS
YNERT	weight moment of inertia of ship or model
ZIMAG	sine term of heaving motion
ZNULL	amplitude of heaving motion
ZREAL	cosine term of heaving motion

Description

This computer program was originally written by K. Haslum[19] and subsequently debugged and completed with the aid of L. Vassilopons[7]. The program has the ability to compute shearing forces and bending moments at any station of a ship or model encountering regular waves. Subroutine BENDSH which essentially performs the above task, was always bypassed in the main computation cycle through the inclusion of a proper control card.

This program is a computer alogorithm of the step-by-step procedure outlined in (8) for the calculation of ship (model) motions and bending moments on the basis of the Korvin-Krovkovsky linear theory of pitching and heaving. Since the program is extensively described in (19), only a brief description of its MAIN program and Subroutines is given.

MAIN Program

The purpose of the MAIN program is to perform certain minor calculations, control the computation cycle from subroutine to subroutine and process all input and output data.

The program output capabilities come under three options, of which the present investigation has made sole use of option No. 1. The program computes motions only and assumes knowledge of radius of gyration.

The main variable for the program is the wavelength and the basic computation cycle repeats the fundamental loop, first for different wavelengths and then returns if the ship speed is changed. For this investigation the ship speed was zero. For the complete calculation the program prints out the wavelength (WL), ship speed (V), and frequency of encounter (OMAGAE). The units

are consistent and correspond to those chosen in the first READ statement. (See Description of Input Data).

Subroutine ADMAB

This subroutine, obtained from the staff of the Davidson Laboratory of the Stevens Institute of Technology, calculates according to Grim's theory[16],

a) the added mass per unit length at each station, which is designated as QUANT(I), and,

b) the ratio of the amplitude of the emitted wave to the amplitude of heave at each station, which is designated as ABAR(I).

Although individually checked for normal Lewis ship sections, the range of the numerical applicability of the subroutine has not been thoroughly examined.

Subroutine COEFF

This subroutine evaluates numerically the expressions (5) for the coefficients of the equations of motion. The correspondence between coefficients and program variables is shown below:

$$\begin{bmatrix} a & b & c \\ d & e & g \\ D & E & G \\ A & B & C \end{bmatrix} = \begin{bmatrix} \mathrm{ADDA(1)} & \mathrm{BEEB(1)} & \mathrm{CGGC(1)} \\ \mathrm{ADDA(2)} & \mathrm{BEEB(2)} & \mathrm{CGGC(2)} \\ \mathrm{ADDA(3)} & \mathrm{BEEB(3)} & \mathrm{CGGC(3)} \\ \mathrm{ADDA(4)} & \mathrm{BEEB(4)} & \mathrm{CGGC(4)} \end{bmatrix}$$

The damping coefficient at each station, denoted by ENOX(I) is obtained from:

$$N(\xi) = \frac{\rho g^2 (\bar{A})^2}{\omega_{ee}^3}$$

where $\bar{A}$ is the quantity designated in subroutine ADMAG as ABAR(I) and the remaining symbols have their usual meaning. The numerical integrations are performed by subroutine SIMPS with an integration interval H = DX1.

Subroutine EXCITE

Subroutine EXCITE computes the excitation force and moment as discussed in Appendix B. The elemental excitation force at a given ship station is computed from equation (3) by splitting the above expression into two parts. The first designated CXFST(I) is in phase with cos $\omega_e t$ and is given by the first bracketed term of equation (3). The second designates SXFST(I) is in phase with sin $\omega_e t$ and is given by the second bracketed term of equation (3). The quantities ϕ_1 and ϕ_2 of equation (3) are correspondingly referred to as FKLAM and SKLAM(I). SKLAM(I) is conveniently subscripted for subsequent utilization in subroutine BENDSH if the computation of bending moments is also required. The total excitation force and moment are finally obtained from equation (4) by integrating over the ship length the appropriate elemental values using subroutine SIMPS with H = DXI.

Subroutine MOTION

Whenever the main program calls this subroutine, the excitation terms and the coefficients of the equations of motion (1) are already available and hence the heaving and pitching motion amplitudes and phase angles can readily be determined. Subroutine MOTION performs this task by first expressing the set (9) in the following form:

$$\bar{F} = F_r + iF_i$$

$$\bar{M} = M_r + iM_i$$

$$P = P_r + iP_i$$

$$Q = Q_r + iQ_i$$

$$R = R_r + iR_i$$

$$S = S_r + iS_i$$

The various products in the set (8) are then evaluated as shown below:

$$\overline{MQ} = (M_rQ_r - M_iQ_i) + i(M_rQ_i + M_iQ_r)$$

$$\overline{FS} = (F_rS_r - F_iS_i) + i(F_rS_i + F_iS_r)$$

$$QR = (Q_rR_r - Q_iR_i) + i(Q_rR_i + Q_iR_r)$$

$$\overline{PS} = (P_rS_r - P_iS_i) + i(P_rS_i + P_iS_r)$$

$$\overline{FR} = (F_rR_r - F_iR_i) + i(F_rR_i + F_iR_r)$$

$$MP = (M_rP_r - M_iP_i) + i(M_rP_i + M_iP_r)$$

so that (8) can finally be computed from

$$\bar{z} = ZREAL - iZIMAG$$

$$\bar{\Theta} = TREAL - iTIMAG$$

where

$$ZREAL = \frac{AC + BD}{C^2 + D^2}$$

$$ZIMAG = \frac{AD - BC}{C^2 + D^2}$$

$$TREAL = \frac{BC + FD}{C^2 + D^2}$$

$$TIMAG = \frac{ED - FC}{C^2 + D^2}$$

and

$$A = M_rQ_r - M_iQ_i - F_rS_r + F_iS_i$$

$$B = M_rQ_i + M_iQ_r - F_rS_i - F_iS_r$$

$$C = Q_rR_r - Q_iR_i - P_rS_r + P_iS_i$$

$$D = Q_rR_i + Q_iR_r - P_rS_i - P_iS_r$$

$$E = F_rR_r - F_iR_i - M_rP_r + M_iP_i$$

$$F = F_iR_r + F_rR_i - M_rP_i - M_iP_r$$

The amplitudes and phase angles of heaving and pitching motions are finally computed with equations (11) and (12), i.e.,

$$\bar{z}_o = \sqrt{(ZREAL)^2 + (ZIMAG)^2}$$

$$\Theta_o = \sqrt{(TREAL)^2 + (TIMAG)^2}$$

and

$$\delta = \arctan\left\{-\frac{ZIMAG}{ZREAL}\right\}$$

$$\varepsilon = \arctan\left\{-\frac{TIMAG}{TREAL}\right\}$$

The correspondence between program variables and the quantities referred to above is as follows:

$$\begin{bmatrix} P_r & P_i \\ F_r & F_i \\ Q_r & Q_i \\ R_r & R_i \\ M_r & M_i \\ S_r & S_i \end{bmatrix} = \begin{bmatrix} TR(1) & TI(1) \\ TR(2) & TI(2) \\ TR(3) & TI(3) \\ TR(4) & TI(4) \\ TR(5) & TI(5) \\ TR(6) & TI(6) \end{bmatrix}$$

and

$$\begin{bmatrix} E & F \\ C & D \\ A & B \end{bmatrix} = \begin{bmatrix} UR(3) & UI(3) \\ UR(4) & UI(4) \\ UR(5) & UI(5) \end{bmatrix}$$

It should be noted that TR(2), TI(2), TR(5) and TI(5) are furnished by subroutine EXCITE.

Subroutine BENDSH

For a complete description of this subroutine the interested reader is referred to (19), which presents the basic analytical treatment involved in the computation of ship bending moments in regular waves. Since this subroutine is at present not used by the computer program under description, we shall refrain from further details.

Subroutine SIMPS

This subroutine is an integrator and calculates numerically various integrals and areas under curves by using Simpson's rule. At any stage of the computation cycle, the number of ordinates furnished to this subroutine must be odd. Thus any integral is evaluated in accord with:

$$\int_a^b f(x)dx = \frac{H}{3} [Y_1 + 4Y_2 + 2Y_3 + \ldots + 4Y_N + Y_{N+1}]$$

where Y(I) are the integrand ordinates and I rises from 1 to J. Y(I), H and J must be preset appropriately to ensure that J is an odd number.

Description of Input Data

The MAIN program includes six READ statements, numbered 1001 - 1006, whose purpose is to (a) transmit the basic input information required for the

computations and (b) incorporate the control cards which decide on the path of the computation and subsequently the form in which the output information is to be given.

Unless specifically stated in the following, numerical data must be of the floating point type. Any consistent system of units may be used, the decision being made by the user for the input variables of the first READ statement (No. 1001). At the end of the FORTRAN or binary deck and after the *DATA card, the basic information for the computations should be given in the following order, one card per READ statement, unless otherwise stated:

a) <u>READ statement 1001, (I10,4F10.4)</u>

1) N = number of stations the ship is divided into. This number is also equal to the highest station number when the latter runs from 0 at the F.P. through N at the A.P. N must be an <u>integer</u> and also, due to the structure of subroutine SIMPS, it must be <u>even</u>. Unless the DIMENSION statements are increased, N should always be less than or equal to 20.

2) BPL = length between perpendiculars of ship or model.

3) GAMMA = specific weight of water

4) GRAV = gravitational acceleration

5) DISPL = displacement of ship or model

b) <u>READ statement 1002, (3F10.4)</u>

This statement requires a number of cards equal to N + 1 giving, for each station starting from the F.P., the following information per card:

1) BSTAR(I) = full beam (breadth) at that station

2) SECOE(I) = sectional area at that station divided by the area of the circumscribing rectangle at that station.

3) DRAFT(I) = actual depth (draft) of section at that station.

c) READ statement 1003, (2F20.4)

This card must always be included since it is a control card which dictates the computer to bypass subroutine BENDSH. The following information is assumed known and must, therefore, be given:

1) RADGYR = radius of gyration of ship or model

2) XI(I) = distance of center of gravity of ship or model from the F.P.

To compute bending moment, use a blank card for this READ statement.

d) READ statement 1004

This statement is never encountered in the computations described herein; therefore no input card should be included for this statement.

e) READ statement 1005, (3I10)

The input card to this statement must always be included since the printed information serves as a controller to the program. Ordinarily, MINKRI, MAXCRI and INCRES are input variables for subroutine BENDSH which, however, is never used in the present computations. For this reason, the following numerical values must be given so as to instruct the computer to bypass BENDSH and avoid related calculations:

MINKRI = -1

MAXKRI = 1

INCRES = 1

f) <u>READ statement 1006, (7F10.4)</u>

1) WA = wave amplitude,

2) SWL = shortest wave length,

3) BWL = longest wave length,

4) DELWL = increment in wave length from SWL to BWL,

5) VMIN = slowest speed,

6) VMAx = highest speed,

(units consistent with READ statement 1001).

7) DELV = increment in speed from VMIN to VMAX.

Description of Output Data

The program prints out the absolute heave and pitch amplitudes, the non-dimensional amplitudes, the cosine term, the sine term, and the phase angles. The particular modification of this program used, computes relative bow motion (REBM). Only the heaving and pitching non-dimensionalized amplitudes were utilized in this investigation.

Input and Output Data

Catamaran Model - Directly Ahead Seas

Input

```
      EXECUTION
      20     4.8000   62.4000   32.2000        48.8050
  0.         0.         0.
   .5200      .7625      .1875
   .6156      .7940      .2625
   .6750      .8290      .2781
   .7000      .8350      .3000
   .7000      .8350      .3000
   .7000      .8350      .3000
   .7000      .8350      .3000
   .7000      .8350      .3000
   .7000      .8350      .3000
   .7000      .8350      .3000
   .7000      .8350      .3000
   .7000      .8350      .3000
   .7000      .8350      .3000
   .7000      .8350      .3000
   .7000      .8350      .3000
   .7000      .8350      .3000
   .6750      .8290      .2781
   .6156      .7940      .2625
   .5200      .7625      .1875
  0.         0.         0.
ENTER RADGYR AND OTHER DATA NOW
              .9065               2.4000
       0          0          0
   .1250      .7500    10.0000     .2500    0.         0.         0.
```

FROUD	V(FT/SEC)	V(KNOTS)	STATION						
0.	0.	0.	0						
WL/LBP	OMEGAE	BEND(FT-T)			AMPL	NON-DIM.	COS-TERM	SIN-TERM	PHASE
.1563	16.4243	0.	0.						
				HEAVE(FT)	.0003	.0021	-.0003	-.0000	1.4696
				PITCH(DEG)	.0007	.0006	.0001	-.0006	-80.3749
				PITCH-HEAVE					
				REBM(FT)	.1255	1.0039	.1189	.0402	18.6795
.2083	14.2239	0.	0.						
				HEAVE(FT)	.0008	.0067	-.0007	-.0004	31.3260
				PITCH(DEG)	.0023	.0030	-.0011	.0021	-61.6881
				PITCH-HEAVE					
				REBM(FT)	.1306	1.0449	.0768	-.1056	-53.9646
.2604	12.7222	0.	0.						
				HEAVE(FT)	.0013	.0101	.0011	.0006	29.9758
				PITCH(DEG)	.0070	.0112	.0022	-.0067	-71.9625
				PITCH-HEAVE					
				REBM(FT)	.1415	1.1324	-.0665	.1249	-61.9637
.3125	11.6137	0.	0.						
				HEAVE(FT)	.0032	.0259	.0026	.0019	35.3157
				PITCH(DEG)	.0111	.0211	.0014	.0110	82.6997
				PITCH-HEAVE					
				REBM(FT)	.1518	1.2143	-.0795	-.1293	58.4223
.3646	10.7522	0.	0.						
				HEAVE(FT)	.0059	.0469	-.0054	-.0022	22.5370
				PITCH(DEG)	.0165	.0367	.0083	.0142	59.5968
				PITCH-HEAVE					
				REBM(FT)	.1404	1.1233	.0758	-.1182	-57.3402
.4167	10.0578	0.	0.						
				HEAVE(FT)	.0130	.1043	-.0127	-.0027	12.1416
				PITCH(DEG)	.0051	.0131	-.0041	-.0031	37.5742
				PITCH-HEAVE					
				REBM(FT)	.1496	1.1968	.1414	.0489	19.0713
.4688	9.4826	0.	0.						
				HEAVE(FT)	.0076	.0605	-.0076	.0005	-3.5060
				PITCH(DEG)	.0227	.0651	-.0201	-.0106	27.6789
				PITCH-HEAVE					
				REBM(FT)	.1753	1.4023	.1067	.1391	52.5026
.5208	8.9960	0.	0.						
				HEAVE(FT)	.0081	.0644	.0076	-.0026	-18.6711
				PITCH(DEG)	.0272	.0864	-.0254	-.0096	20.7904
				PITCH-HEAVE					
				REBM(FT)	.1485	1.1876	.0222	.1468	81.3968
.5729	8.5773	0.	0.						
				HEAVE(FT)	.0236	.1889	.0196	-.0132	-33.9078
				PITCH(DEG)	.0219	.0768	-.0211	-.0062	16.3230
				PITCH-HEAVE					
				REBM(FT)	.1292	1.0336	-.0587	.1151	-62.9688
.6250	8.2122	0.	0.						
				HEAVE(FT)	.0326	.2611	.0229	-.0233	-45.4733
				PITCH(DEG)	.0117	.0449	-.0114	-.0027	13.2161
				PITCH-HEAVE					
				REBM(FT)	.1332	1.0655	-.1143	.0683	-30.8692
.6771	7.8900	0.	0.						
				HEAVE(FT)	.0347	.2780	.0205	-.0281	-53.9425
				PITCH(DEG)	.0002	.0008	.0002	.0001	20.7616
				PITCH-HEAVE					
				REBM(FT)	.1468	1.1741	-.1455	.0189	-7.3903
.7292	7.6030	0.	0.						
				HEAVE(FT)	.0319	.2553	.0159	-.0277	-60.0939
				PITCH(DEG)	.0120	.0536	.0118	.0020	9.7107

				PITCH-HEAVE					
				REBM(FT)	.1614	1.2915	-.1593	-.0263	9.3879
.7813	7.3452	0.	0.						
				HEAVE(FT)	.0261	.2085	.0112	-.0235	-64.5819
				PITCH(DEG)	.0228	.1091	.0226	.0033	8.3830
				PITCH-HEAVE					
				REBM(FT)	.1740	1.3919	-.1617	-.0641	21.6297
.8333	7.1119	0.	0.						
				HEAVE(FT)	.0186	.1488	.0070	-.0172	-67.8019
				PITCH(DEG)	.0323	.1645	.0320	.0041	7.3623
				PITCH-HEAVE					
				REBM(FT)	.1832	1.4657	-.1574	-.0938	30.8082
.8854	6.8996	0.	0.						
				HEAVE(FT)	.0104	.0834	.0036	-.0098	-69.6960
				PITCH(DEG)	.0403	.2181	.0400	.0046	6.5418
				PITCH-HEAVE					
				REBM(FT)	.1890	1.5117	-.1491	-.1161	37.8896
.9375	6.7052	0.	0.						
				HEAVE(FT)	.0021	.0169	.0009	-.0019	-64.0479
				PITCH(DEG)	.0469	.2689	.0467	.0048	5.8668
				PITCH-HEAVE					
				REBM(FT)	.1916	1.5327	-.1390	-.1319	43.5042
.9896	6.5264	0.	0.						
				HEAVE(FT)	.0061	.0489	-.0012	.0060	-79.0468
				PITCH(DEG)	.0523	.3165	.0521	.0048	5.3018
				PITCH-HEAVE					
				REBM(FT)	.1916	1.5329	-.1280	-.1425	48.0659
1.0417	6.3611	0.	0.						
				HEAVE(FT)	.0139	.1115	-.0027	.0137	-78.6329
				PITCH(DEG)	.0567	.3608	.0565	.0048	4.8224
				PITCH-HEAVE					
				REBM(FT)	.1896	1.5169	-.1171	-.1491	51.8510
1.0938	6.2078	0.	0.						
				HEAVE(FT)	.0213	.1706	-.0039	.0210	-79.3619
				PITCH(DEG)	.0601	.4017	.0599	.0046	4.4108
				PITCH-HEAVE					
				REBM(FT)	.1861	1.4889	-.1066	-.1525	55.0488
1.1458	6.0651	0.	0.						
				HEAVE(FT)	.0282	.2258	-.0048	.0278	-80.1787
				PITCH(DEG)	.0628	.4394	.0626	.0044	4.0540
				PITCH-HEAVE					
				REBM(FT)	.1815	1.4523	-.0968	-.1536	57.7917
1.1979	5.9318	0.	0.						
				HEAVE(FT)	.0346	.2770	-.0054	.0342	-80.9467
				PITCH(DEG)	.0648	.4741	.0646	.0042	3.7420
				PITCH-HEAVE					
				REBM(FT)	.1762	1.4098	-.0876	-.1529	60.1749
1.2500	5.8069	0.	0.						
				HEAVE(FT)	.0406	.3244	-.0059	.0401	-81.6416
				PITCH(DEG)	.0662	.5060	.0661	.0040	3.4671
				PITCH-HEAVE					
				REBM(FT)	.1704	1.3635	-.0793	-.1509	62.2687
1.3021	5.6895	0.	0.						
				HEAVE(FT)	.0460	.3681	-.0062	.0456	-82.2635
				PITCH(DEG)	.0673	.5353	.0672	.0038	3.2234
				PITCH-HEAVE					
				REBM(FT)	.1644	1.3152	-.0717	-.1479	64.1255
1.3542	5.5791	0.	0.						
				HEAVE(FT)	.0511	.4084	-.0064	.0506	-82.8193
				PITCH(DEG)	.0679	.5622	.0678	.0036	3.0059
				PITCH-HEAVE					

				REBM(FT)	.1583	1.2660	-.0649	-.1443	65.7857
1.4063	5.4748	0.	0.						
				HEAVE(FT)	.0557	.4455	-.0065	.0553	-83.3166
				PITCH(DEG)	.0683	.5870	.0682	.0033	2.8110
				PITCH-HEAVE					
				REBM(FT)	.1521	1.2168	-.0587	-.1403	67.2808
1.4583	5.3761	0.	0.						
				HEAVE(FT)	.0600	.4796	-.0065	.0596	-83.7630
				PITCH(DEG)	.0684	.6098	.0683	.0031	2.6354
				PITCH-HEAVE					
				REBM(FT)	.1460	1.1683	-.0532	-.1360	68.6356
1.5104	5.2826	0.	0.						
				HEAVE(FT)	.0639	.5110	-.0065	.0635	-84.1648
				PITCH(DEG)	.0683	.6308	.0683	.0030	2.4764
				PITCH-HEAVE					
				REBM(FT)	.1401	1.1210	-.0482	-.1316	69.8699
1.5625	5.1938	0.	0.						
				HEAVE(FT)	.0675	.5400	-.0064	.0672	-84.5279
				PITCH(DEG)	.0681	.6503	.0680	.0028	2.3321
				PITCH-HEAVE					
				REBM(FT)	.1344	1.0751	-.0438	-.1271	71.0002
1.6146	5.1094	0.	0.						
				HEAVE(FT)	.0708	.5667	-.0063	.0706	-84.8571
				PITCH(DEG)	.0677	.6682	.0677	.0026	2.2005
				PITCH-HEAVE					
				REBM(FT)	.1289	1.0308	-.0397	-.1226	72.0397
1.6667	5.0289	0.	0.						
				HEAVE(FT)	.0739	.5914	-.0062	.0737	-85.1565
				PITCH(DEG)	.0672	.6848	.0672	.0024	2.0802
				PITCH-HEAVE					
				REBM(FT)	.1235	.9883	-.0361	-.1181	72.9994
1.7188	4.9521	0.	0.						
				HEAVE(FT)	.0768	.6141	-.0061	.0765	-85.4296
				PITCH(DEG)	.0667	.7002	.0666	.0023	1.9698
				PITCH-HEAVE					
				REBM(FT)	.1185	.9476	-.0329	-.1138	73.8887
1.7708	4.8787	0.	0.						
				HEAVE(FT)	.0794	.6352	-.0060	.0792	-85.6796
				PITCH(DEG)	.0660	.7145	.0660	.0022	1.8683
				PITCH-HEAVE					
				REBM(FT)	.1136	.9088	-.0299	-.1096	74.7154
1.8229	4.8085	0.	0.						
				HEAVE(FT)	.0818	.6548	-.0058	.0816	-85.9090
				PITCH(DEG)	.0653	.7277	.0653	.0020	1.7746
				PITCH-HEAVE					
				REBM(FT)	.1090	.8718	-.0273	-.1055	75.4861
1.8750	4.7413	0.	0.						
				HEAVE(FT)	.0841	.6729	-.0057	.0839	-86.1201
				PITCH(DEG)	.0646	.7401	.0646	.0019	1.6880
				PITCH-HEAVE					
				REBM(FT)	.1046	.8365	-.0249	-.1015	76.2067
1.9271	4.6768	0.	0.						
				HEAVE(FT)	.0862	.6897	-.0055	.0860	-86.3148
				PITCH(DEG)	.0638	.7516	.0638	.0018	1.6078
				PITCH-HEAVE					
				REBM(FT)	.1004	.8030	-.0228	-.0978	76.8821
1.9792	4.6148	0.	0.						
				HEAVE(FT)	.0882	.7054	-.0054	.0880	-86.4949
				PITCH(DEG)	.0630	.7624	.0630	.0017	1.5333
				PITCH-HEAVE					
				REBM(FT)	.0964	.7712	-.0208	-.0941	77.5165

```
  2.0313  4.5553    0.       0.
                                     HEAVE(FT)     .0900      .7199     -.0052      .0898  -86.6617
                                    PITCH(DEG)     .0622      .7724      .0622      .0016    1.4640
                                   PITCH-HEAVE
                                      REBM(FT)     .0926      .7409     -.0191     -.0906   78.1137
  2.0833  4.4980    0.       0.
                                     HEAVE(FT)     .0917      .7335     -.0051      .0915  -86.8166
                                    PITCH(DEG)     .0614      .7818      .0614      .0015    1.3993
                                   PITCH-HEAVE
                                      REBM(FT)     .0890      .7122     -.0175     -.0873   78.6771
 ENTER RADGYR AND CTHER DATA NOW
```

ALVIN Model - Directly Ahead Seas

Input

```
       EXECUTION
       20     1.1000    62.4000    32.2000           4.8200
   0.         0.         0.
    .2763      .8060      .2687
    .3763      .8120      .3122
    .4170      .8530      .3300
    .4160      .8500      .3460
    .4020      .8440      .3465
    .4015      .8350      .3410
    .3957      .8290      .3360
    .3863      .8264      .3300
    .3765      .8238      .3225
    .3632      .8210      .3165
    .3424      .8180      .3070
    .2982      .8150      .2950
    .2719      .8120      .2740
    .2425      .7854      .2507
    .2082      .7854      .2292
    .1542      .7854      .2042
    .0933      .7854      .1935
    .2150      .7854      .2341
    .2265      .7854      .2341
   0.         0.         0.
ENTER RADGYR AND OTHER DATA NOW
               .2420                .4270
        0          0          0



    .1250      .7500    10.0000      .2500     0.         0.         0.
```

FROUDE	V(FT/SEC)	V(KNOTS)	STATION
0.	0.	0.	C

WL/LBP	OMEGAE	BEND(FT-T)			AMPL	NON-DIM.	COS-TERM	SIN-TERM	PHASE
.6818	16.4243	0.	C.						
				HEAVE(FT)	.0013	.0106	-.0002	.0013	-80.7696
				PITCH(DEG)	.0101	.0096	.0054	.0084	57.2074
				PITCH-HEAVE					
				REBM(FT)	.1275	1.0201	-.1274	.0048	-2.1742
.9091	14.2239	0.	C.						
				HEAVE(FT)	.0040	.0322	-.0026	.0030	-49.0589
				PITCH(DEG)	.0382	.0486	-.0259	.0281	-47.3626
				PITCH-HEAVE					
				REBM(FT)	.1366	1.0926	-.0379	-.1312	73.8927
1.1364	12.7222	0.	C.						
				HEAVE(FT)	.0076	.0609	-.0074	-.0018	13.4694
				PITCH(DEG)	.1887	.3002	-.1361	.1306	-43.8091
				PITCH-HEAVE					
				REBM(FT)	.2268	1.8141	.1177	-.1938	-58.7259
1.3636	11.6137	0.	C.						
				HEAVE(FT)	.0395	.3156	-.0299	-.0257	40.7144
				PITCH(DEG)	.5095	.9730	.0183	.5091	87.9368
				PITCH-HEAVE					
				REBM(FT)	.3729	2.9834	.1038	-.3582	-73.8374
1.5909	10.7522	0.	C.						
				HEAVE(FT)	.1047	.8380	-.1017	-.0252	13.9094
				PITCH(DEG)	.3947	.8755	.3085	.2462	38.5950
				PITCH-HEAVE					
				REBM(FT)	.1779	1.4233	.0354	-.1744	-78.5238
1.8182	10.0578	0.	C.						
				HEAVE(FT)	.1779	1.4228	-.1664	.0629	-20.7104
				PITCH(DEG)	.2523	.6426	.2928	.1627	40.1660
				PITCH-HEAVE					
				REBM(FT)	.2561	2.0491	.2776	-.1846	-46.0982
2.0455	9.4826	0.	C.						
				HEAVE(FT)	.1868	1.4941	-.1163	.1462	-51.4992
				PITCH(DEG)	.2743	.7869	.1957	.1923	44.5002
				PITCH-HEAVE					
				REBM(FT)	.2903	2.3229	.1291	-.2600	-63.5957
2.2727	8.9960	0.	C.						
				HEAVE(FT)	.1691	1.3528	-.0669	.1553	-66.7110
				PITCH(DEG)	.2755	.8760	.2160	.1709	38.3443
				PITCH-HEAVE					
				REBM(FT)	.2462	1.9700	.0670	-.2370	-74.2120
2.5000	8.5773	0.	C.						
				HEAVE(FT)	.1557	1.2469	-.0428	.1497	-74.0322
				PITCH(DEG)	.2605	.9120	.2171	.1439	33.5470
				PITCH-HEAVE					
				REBM(FT)	.2037	1.8296	.0392	-.1999	-78.9041
2.7273	8.2122	0.	C.						
				HEAVE(FT)	.1473	1.1788	-.0305	.1441	-78.0445
				PITCH(DEG)	.2434	.9298	.2102	.1227	30.2785
				PITCH-HEAVE					
				REBM(FT)	.1712	1.3659	.0266	-.1692	-81.0825
2.9545	7.8900	0.	C.						
				HEAVE(FT)	.1420	1.1358	-.0234	.1400	-80.5110
				PITCH(DEG)	.2274	.9409	.2008	.1086	27.9553
				PITCH-HEAVE					
				REBM(FT)	.1466	1.1732	.0202	-.1453	-82.0993
3.1818	7.6030	0.	C.						
				HEAVE(FT)	.1384	1.1089	-.0189	.1371	-82.1641
				PITCH(DEG)	.2130	.9495	.2911	.0941	26.2280

				PITCH-HEAVE REBM(FT)	.1276	1.0208	.0164	-.1265	-82.8014
3.4091	7.3452	0.	0.						
				HEAVE(FT)	.1359	1.0889	-.0157	.1349	-83.3456
				PITCH(DEG)	.2003	.9564	.1817	.0843	24.8850
				PITCH-HEAVE REBM(FT)	.1124	.8955	.0140	-.1116	-82.8342
3.6364	7.1119	0.	0.						
				HEAVE(FT)	.1341	1.0725	-.0135	.1334	-84.2221
				PITCH(DEG)	.1890	.9624	.1729	.0763	23.8118
				PITCH-HEAVE REBM(FT)	.1002	.8013	.0123	-.0994	-82.9270
3.8636	6.8996	0.	0.						
				HEAVE(FT)	.1327	1.0618	-.0117	.1322	-84.9226
				PITCH(DEG)	.1788	.9676	.1647	.0697	22.9315
				PITCH-HEAVE REBM(FT)	.0900	.7203	.0111	-.0894	-82.9467
4.0909	6.7052	0.	0.						
				HEAVE(FT)	.1317	1.0538	-.0104	.1313	-85.4764
				PITCH(DEG)	.1697	.9722	.1571	.0641	22.1951
				PITCH-HEAVE REBM(FT)	.0816	.6525	.0100	-.0809	-82.9295
4.3182	6.5264	0.	0.						
				HEAVE(FT)	.1309	1.0473	-.0093	.1306	-85.9309
				PITCH(DEG)	.1614	.9763	.1501	.0593	21.5692
				PITCH-HEAVE REBM(FT)	.0744	.5950	.0092	-.0738	-82.8953
4.5455	6.3611	0.	0.						
				HEAVE(FT)	.1303	1.0422	-.0084	.1300	-86.3110
				PITCH(DEG)	.1539	.9799	.1437	.0552	21.0300
				PITCH-HEAVE REBM(FT)	.0682	.5457	.0085	-.0677	-82.8551
4.7727	6.2078	0.	0.						
				HEAVE(FT)	.1298	1.0381	-.0076	.1295	-86.6338
				PITCH(DEG)	.1471	.9832	.1377	.0517	20.5806
				PITCH-HEAVE REBM(FT)	.0629	.5031	.0079	-.0624	-82.8153
5.0000	6.0651	0.	0.						
				HEAVE(FT)	.1293	1.0346	-.0070	.1291	-86.9113
				PITCH(DEG)	.1408	.9862	.1322	.0485	20.1480
				PITCH-HEAVE REBM(FT)	.0582	.4659	.0073	-.0578	-82.7793
5.2273	5.9318	0.	0.						
				HEAVE(FT)	.1290	1.0318	-.0064	.1288	-87.1525
				PITCH(DEG)	.1351	.9888	.1271	.0457	19.7824
				PITCH-HEAVE REBM(FT)	.0542	.4332	.0068	-.0537	-82.7487
5.4545	5.8069	0.	0.						
				HEAVE(FT)	.1287	1.0294	-.0059	.1285	-87.3640
				PITCH(DEG)	.1298	.9912	.1223	.0432	19.4583
				PITCH-HEAVE REBM(FT)	.0505	.4043	.0064	-.0501	-82.7245
5.6818	5.6895	0.	0.						
				HEAVE(FT)	.1284	1.0273	-.0055	.1283	-87.5510
				PITCH(DEG)	.1248	.9934	.1179	.0410	19.1637
				PITCH-HEAVE REBM(FT)	.0473	.3786	.0060	-.0469	-82.7066
5.9091	5.5791	0.	0.						
				HEAVE(FT)	.1282	1.0255	-.0051	.1281	-87.7174
				PITCH(DEG)	.1203	.9954	.1138	.0390	18.8996
				PITCH-HEAVE					

				REBM(FT)	.0445	.3557	.0057	-.0441	-82.6951
6.1364	5.4748	0.	C.	HEAVE(FT)	.1280	1.0239	-.0048	.1279	-87.8663
				PITCH(DEG)	.1160	.9972	.1099	.0371	18.6602
				PITCH-HEAVE					
				REBM(FT)	.0419	.3350	.0053	-.0415	-82.6897
6.3636	5.3761	0.	C.	HEAVE(FT)	.1278	1.0225	-.0045	.1277	-88.0002
				PITCH(DEG)	.1121	.9989	.1063	.0355	18.4422
				PITCH-HEAVE					
				REBM(FT)	.0395	.3164	.0050	-.0392	-82.6898
6.5909	5.2826	0.	C.	HEAVE(FT)	.1277	1.0213	-.0042	.1276	-88.1213
				PITCH(DEG)	.1084	1.0004	.1029	.0339	18.2430
				PITCH-HEAVE					
				REBM(FT)	.0374	.2995	.0048	-.0371	-82.6950
6.8182	5.1938	0.	C.	HEAVE(FT)	.1275	1.0202	-.0039	.1275	-88.2312
				PITCH(DEG)	.1049	1.0018	.0997	.0325	18.0602
				PITCH-HEAVE					
				REBM(FT)	.0355	.2841	.0045	-.0352	-82.7048
7.0455	5.1094	0.	C.	HEAVE(FT)	.1274	1.0192	-.0037	.1273	-88.3313
				PITCH(DEG)	.1017	1.0031	.0967	.0312	17.8920
				PITCH-HEAVE					
				REBM(FT)	.0338	.2701	.0043	-.0335	-82.7189
7.2727	5.0289	0.	C.	HEAVE(FT)	.1273	1.0182	-.0035	.1272	-88.4229
				PITCH(DEG)	.0986	1.0043	.0939	.0300	17.7367
				PITCH-HEAVE					
				REBM(FT)	.0321	.2572	.0041	-.0319	-82.7368
7.5000	4.9521	0.	C.	HEAVE(FT)	.1272	1.0174	-.0033	.1271	-88.5069
				PITCH(DEG)	.0957	1.0065	.0912	.0289	17.5931
				PITCH-HEAVE					
				REBM(FT)	.0307	.2454	.0039	-.0304	-82.7581
7.7273	4.8787	0.	C.	HEAVE(FT)	.1271	1.0167	-.0031	.1270	-88.5841
				PITCH(DEG)	.0930	1.0065	.0887	.0279	17.4597
				PITCH-HEAVE					
				REBM(FT)	.0293	.2345	.0037	-.0291	-82.7823
7.9545	4.8085	0.	C.	HEAVE(FT)	.1270	1.0160	-.0030	.1270	-88.6553
				PITCH(DEG)	.0904	1.0075	.0863	.0269	17.2357
				PITCH-HEAVE					
				REBM(FT)	.0281	.2244	.0035	-.0278	-82.8092
8.1818	4.7413	0.	C.	HEAVE(FT)	.1269	1.0153	-.0028	.1269	-88.7211
				PITCH(DEG)	.0880	1.0084	.0841	.0261	17.2201
				PITCH-HEAVE					
				REBM(FT)	.0269	.2151	.0034	-.0267	-82.8385
8.4091	4.6768	0.	C.	HEAVE(FT)	.1268	1.0147	-.0027	.1268	-88.7821
				PITCH(DEG)	.0857	1.0092	.0819	.0252	17.1121
				PITCH-HEAVE					
				REBM(FT)	.0258	.2065	.0032	-.0256	-82.8698
8.6364	4.6148	0.	C.	HEAVE(FT)	.1268	1.0142	-.0026	.1267	-88.8388
				PITCH(DEG)	.0835	1.0100	.0798	.0244	17.0111
				PITCH-HEAVE					
				REBM(FT)	.0248	.1984	.0031	-.0246	-82.9030

8.8636	4.5553	0.	C.	HEAVE(FT)	.1267	1.0137	-.0025	.1267	-88.8915
				PITCH(DEG)	.0814	1.0107	.0779	.0237	16.9163
				PITCH-HEAVE					
				REBM(FT)	.C239	.1909	.0029	-.0237	-82.9377
9.C909	4.4980	0.	C.	HEAVE(FT)	.1266	1.0132	-.0023	.1266	-88.9406
				PITCH(DEG)	.0794	1.0124	.0760	.0230	16.8273
				PITCH-HEAVE					
				REBM(FT)	.C230	.1839	.0028	-.0228	-82.9738

ENTER RADCYR AND OTHER DATA NOW

ALVIN Model - Directly Astern Seas

Input

```
        EXECUTION
        20      1.1000   62.4000   32.2000          4.8200
   0.          0.         0.
     .2265      .7854     .2341
     .2150      .7854     .2341
     .0933      .7854     .1935
     .1542      .7854     .2042
     .2082      .7854     .2292
     .2425      .7854     .2507
     .2719      .8120     .2740
     .2982      .8150     .2950
     .3424      .8180     .3070
     .3632      .8210     .3165
     .3765      .8238     .3225
     .3863      .8264     .3300
     .3957      .8290     .3360
     .4015      .8350     .3410
     .4020      .8440     .3465
     .4160      .8500     .3460
     .4170      .8530     .3300
     .3763      .8120     .3122
     .2763      .8060     .2687
   0.          0.         0.
ENTER RADGYR AND OTHER DATA NOW
                .2420                .5730
          0         0         0
     .1250      .7500    10.0000     .2500     0.         0.         0.
```

FROUD	V(FT/SEC)	V(KNOTS)	STATICN						
0.	0.	0.	C						
WL/LBP	CMEGAE	BEND(FT-T)			AMPL	NON-DIM.	COS-TERM	SIN-TERM	PHASE
.6818	16.4243	0.	0.						
				HEAVE(FT)	.0016	.0131	-.0005	.0015	-71.5279
				PITCH(DEG)	.0134	.0128	.0108	-.0080	-36.3751
				PITCH-HEAVE					
				REBM(FT)	.1251	1.0011	-.0568	-.1115	62.9805
.9091	14.2239	0.	0.						
				HEAVE(FT)	.0061	.0484	.0042	.0043	45.7422
				PITCH(DEG)	.0560	.0713	-.0440	-.0346	38.1433
				PITCH-HEAVE					
				REBM(FT)	.1234	.9870	.0699	-.1017	-55.4770
1.1364	12.7222	0.	0.						
				HEAVE(FT)	.0290	.2321	.0174	-.0232	-53.0729
				PITCH(DEG)	.2762	.4396	-.2213	.1652	-36.7337
				PITCH-HEAVE					
				REBM(FT)	.2154	1.7236	.1819	-.1154	-32.3806
1.3636	11.6137	0.	0.						
				HEAVE(FT)	.0660	.5281	-.0445	-.0487	47.5639
				PITCH(DEG)	.3361	.6419	.1710	.2893	59.4222
				PITCH-HEAVE					
				REBM(FT)	.1383	1.1065	.0936	-.1018	-47.4187
1.5909	10.7522	0.	0.						
				HEAVE(FT)	.0972	.7774	-.0899	-.0369	22.3133
				PITCH(DEG)	.1939	.4321	.1815	.0683	20.6381
				PITCH-HEAVE					
				REBM(FT)	.1379	1.1031	.1373	.0124	5.1687
1.8182	10.0578	0.	0.						
				HEAVE(FT)	.1588	1.2700	-.1587	.0019	-.6955
				PITCH(DEG)	.0460	.1172	.0362	.0285	38.1859
				PITCH-HEAVE					
				REBM(FT)	.2654	2.1232	.2650	.0143	3.0965
2.0455	9.4826	0.	0.						
				HEAVE(FT)	.1985	1.5881	-.1664	.1082	-33.0306
				PITCH(DEG)	.1641	.4702	-.0029	.1641	-88.9823
				PITCH-HEAVE					
				REBM(FT)	.3131	2.5046	.2838	-.1321	-24.9589
2.2727	8.9960	0.	0.						
				HEAVE(FT)	.1853	1.4828	-.1054	.1524	-55.3280
				PITCH(DEG)	.2244	.7142	.0874	.2067	67.0771
				PITCH-HEAVE					
				REBM(FT)	.2538	2.0307	.1780	-.1810	-45.4862
2.5000	8.5773	0.	0.						
				HEAVE(FT)	.1669	1.3354	-.0666	.1531	-66.4935
				PITCH(DEG)	.2276	.7970	.1393	.1801	52.2801
				PITCH-HEAVE					
				REBM(FT)	.1944	1.5553	.1106	-.1599	-55.3213
2.7273	8.2122	0.	0.						
				HEAVE(FT)	.1546	1.2366	-.0466	.1474	-72.4537
				PITCH(DEG)	.2174	.8306	.1585	.1489	43.2175
				PITCH-HEAVE					
				REBM(FT)	.1531	1.2250	.0764	-.1327	-60.0678
2.9545	7.8900	0.	0.						
				HEAVE(FT)	.1467	1.1737	-.0354	.1424	-76.0460
				PITCH(DEG)	.2050	.8485	.1634	.1238	37.1455
				PITCH-HEAVE					
				REBM(FT)	.1245	.9962	.0575	-.1105	-62.5254
3.1818	7.6030	0.	0.						
				HEAVE(FT)	.1416	1.1325	-.0284	.1387	-78.4356

				PITCH(DEG)	.1931	.8604	.1623	.1045	32.7715
				PITCH-HEAVE					
				REBM(FT)	.1039	.8312	.0458	-.0933	-63.8632
3.4091	7.3452	0.	0.						
				HEAVE(FT)	.1380	1.1044	-.0236	.1380	-80.1444
				PITCH(DEG)	.1821	.8694	.1586	.0895	29.4519
				PITCH-HEAVE					
				REBM(FT)	.0884	.7075	.0379	-.0799	-64.4070
3.6364	7.1119	0.	0.						
				HEAVE(FT)	.1356	1.0845	-.0202	.1340	-81.4326
				PITCH(DEG)	.1722	.8768	.1536	.0777	26.8348
				PITCH-HEAVE					
				REBM(FT)	.0765	.6117	.0323	-.0693	-65.0162
3.8636	6.8996	0.	0.						
				HEAVE(FT)	.1337	1.0699	-.0176	.1326	-82.4422
				PITCH(DEG)	.1632	.8831	.1483	.0682	24.7117
				PITCH-HEAVE					
				REBM(FT)	.0670	.5357	.0281	-.0608	-65.2288
4.0909	6.7052	0.	0.						
				HEAVE(FT)	.1324	1.0590	-.0155	.1315	-83.2570
				PITCH(DEG)	.1551	.8887	.1428	.0605	22.9507
				PITCH-HEAVE					
				REBM(FT)	.0593	.4741	.0247	-.0539	-65.3227
4.3182	6.5264	0.	0.						
				HEAVE(FT)	.1313	1.0506	-.0139	.1306	-83.9296
				PITCH(DEG)	.1478	.8937	.1375	.0541	21.4639
				PITCH-HEAVE					
				REBM(FT)	.0529	.4233	.0221	-.0481	-65.3439
4.5455	6.3611	0.	0.						
				HEAVE(FT)	.1305	1.0440	-.0125	.1299	-84.4948
				PITCH(DEG)	.1411	.8982	.1324	.0487	20.1904
				PITCH-HEAVE					
				REBM(FT)	.0476	.3808	.0199	-.0433	-65.3209
4.7727	6.2078	0.	0.						
				HEAVE(FT)	.1298	1.0387	-.0114	.1293	-84.9767
				PITCH(DEG)	.1350	.9023	.1276	.0441	19.0863
				PITCH-HEAVE					
				REBM(FT)	.0431	.3449	.0180	-.0392	-65.2714
5.0000	6.0651	0.	0.						
				HEAVE(FT)	.1293	1.0344	-.0104	.1289	-85.3924
				PITCH(DEG)	.1294	.9061	.1230	.0402	18.1193
				PITCH-HEAVE					
				REBM(FT)	.0393	.3141	.0165	-.0356	-65.2068
5.2273	5.9318	0.	0.						
				HEAVE(FT)	.1289	1.0308	-.0095	.1285	-85.7545
				PITCH(DEG)	.1242	.9095	.1186	.0369	17.2649
				PITCH-HEAVE					
				REBM(FT)	.0359	.2875	.0151	-.0326	-65.1345
5.4545	5.8069	0.	0.						
				HEAVE(FT)	.1285	1.0279	-.0088	.1282	-86.0727
				PITCH(DEG)	.1195	.9127	.1146	.0339	16.5041
				PITCH-HEAVE					
				REBM(FT)	.0330	.2644	.0139	-.0300	-65.0595
5.6818	5.6895	0.	0.						
				HEAVE(FT)	.1282	1.0254	-.0082	.1279	-86.3542
				PITCH(DEG)	.1151	.9157	.1107	.0314	15.8223
				PITCH-HEAVE					
				REBM(FT)	.0305	.2441	.0129	-.0276	-64.9849
5.9091	5.5791	0.	0.						
				HEAVE(FT)	.1279	1.0232	-.0076	.1277	-86.6048

				PITCH(DEG)	.1110	.9185	.1071	.0291	15.2074
				PITCH-HEAVE REBM(FT)	.0283	.2262	.0120	-.0256	-64.9127
6.1364	5.4748	0.	0.						
				HEAVE(FT)	.1277	1.0214	-.0071	.1275	-86.8292
				PITCH(DEG)	.1072	.9211	.1037	.0271	14.6500
				PITCH-HEAVE REBM(FT)	.0263	.2103	.0112	-.0238	-64.8443
6.3636	5.3761	0.	0.						
				HEAVE(FT)	.1275	1.0198	-.0066	.1273	-87.0311
				PITCH(DEG)	.1036	.9235	.1005	.0253	14.1423
				PITCH-HEAVE REBM(FT)	.0245	.1961	.0104	-.0222	-64.7805
6.5909	5.2826	0.	0.						
				HEAVE(FT)	.1273	1.0183	-.0062	.1271	-87.2136
				PITCH(DEG)	.1003	.9257	.0974	.0237	13.6779
				PITCH-HEAVE REBM(FT)	.0229	.1834	.0098	-.0207	-64.7216
6.8182	5.1938	0.	0.						
				HEAVE(FT)	.1271	1.0171	-.0058	.1270	-87.3791
				PITCH(DEG)	.0972	.9279	.0946	.0223	13.2513
				PITCH-HEAVE REBM(FT)	.0215	.1720	.0092	-.0194	-64.6679
7.0455	5.1094	0.	0.						
				HEAVE(FT)	.1270	1.0160	-.0055	.1269	-87.5259
				PITCH(DEG)	.0942	.9299	.0919	.0210	12.8582
				PITCH-HEAVE REBM(FT)	.0202	.1616	.0087	-.0183	-64.6195
7.2727	5.0289	0.	0.						
				HEAVE(FT)	.1269	1.0150	-.0052	.1268	-87.6676
				PITCH(DEG)	.0915	.9318	.0893	.0198	12.4945
				PITCH-HEAVE REBM(FT)	.0190	.1522	.0082	-.0172	-64.5762
7.5000	4.9521	0.	0.						
				HEAVE(FT)	.1268	1.0141	-.0049	.1267	-87.7939
				PITCH(DEG)	.0889	.9335	.0869	.0187	12.1572
				PITCH-HEAVE REBM(FT)	.0180	.1437	.0077	-.0162	-64.5379
7.7273	4.8787	0.	0.						
				HEAVE(FT)	.1267	1.0133	-.0046	.1266	-87.9059
				PITCH(DEG)	.0864	.9352	.0846	.0177	11.8435
				PITCH-HEAVE REBM(FT)	.0170	.1358	.0073	-.0153	-64.5045
7.9545	4.8085	0.	0.						
				HEAVE(FT)	.1266	1.0126	-.0044	.1265	-88.0167
				PITCH(DEG)	.0841	.9368	.0824	.0168	11.5508
				PITCH-HEAVE REBM(FT)	.0161	.1287	.0069	-.0145	-64.4757
8.1818	4.7413	0.	0.						
				HEAVE(FT)	.1265	1.0119	-.0042	.1264	-88.1155
				PITCH(DEG)	.0819	.9384	.0803	.0160	11.2772
				PITCH-HEAVE REBM(FT)	.0153	.1221	.0066	-.0138	-64.4512
8.4091	4.6768	0.	0.						
				HEAVE(FT)	.1264	1.0113	-.0040	.1263	-88.2068
				PITCH(DEG)	.0798	.9398	.0783	.0153	11.0208
				PITCH-HEAVE REBM(FT)	.0145	.1160	.0063	-.0131	-64.4309
8.6364	4.6148	0.	0.						
				HEAVE(FT)	.1263	1.0107	-.0038	.1263	-88.2916

				PITCH(DEG)	.0778	.9412	.0764	.0146	10.7800
				PITCH-HEAVE REBM(FT)	.0138	.1104	.0060	-.0125	-64.4145
8.8636	4.5553	0.	0.						
				HEAVE(FT)	.1263	1.0102	-.0036	.1262	-88.3704
				PITCH(DEG)	.0759	.9425	.0746	.0139	10.5534
				PITCH-HEAVE REBM(FT)	.0132	.1053	.0057	-.0119	-64.4017
9.0909	4.4980	0.	0.						
				HEAVE(FT)	.1262	1.0097	-.0034	.1262	-88.4438
				PITCH(DEG)	.0741	.9438	.0729	.0133	10.3398
				PITCH-HEAVE REBM(FT)	.0126	.1004	.0054	-.0113	-64.3925

ENTER RADGYR AND OTHER DATA NOW

Listing of Program and Subroutines

```
      THE DYNAMIC BENDING MOMENT IN REGULAR WAVES

      DIMENSION Y(21),TR(6),TI(6),ADDA(4),BEEB(4),CGGC(4),UR(6),UI(6),
     1DMASS(21),QUANT(21),SKLAM(21),BSTAR(21),CXFST(21),SXFST(21),
     2CTFST(21),STFST(21),XI(21),DIX(21),ENOXI(21),DRAFT(21),DWEIGH(21),
     3SECOE(21),ABAR(21)
       COMMON Y,J,SYMPS,DXI,ADDA,BEEB,CGGC,ZREAL,ZIMAG,TREAL,TIMAG,ZNULL,
     1TNULL,DELTA,EPSIL,TR,TI,V,DMASS,QUANT,OMEGAE,SKLAM,KRIT,RO,GRAV,
     2BSTAR,CXFST,SXFST,ALPHA,SHNULL,XI,BETA,BMNULL,GAMMA,DIX,M,WA,WAVEN
     3,CW,ENOXI,SIGMA,TAU,FNULL,EMNULL,DRAFT,DWEIGH,SECOE,TMASS,N,UR,UI,
     4ABAR,PI,SHREAL,SHIMAG,BMREAL,BMIMAG,YNERT,BPL
  900 FORMAT(110,4F10.4)
  901 FORMAT(3F10.4)
  902 FORMAT(F10.4)
      CONTINUE
  904 FORMAT(4F20.3)
  905 FORMAT(2F20.4)
  906 FORMAT(7F10.4)
  907 FORMAT(3110)
  922 FORMAT(120)
  903 FORMAT(F9.4,2F10.4,3F9.4,F8.4)
  909 FORMAT(55H FROUDE WL/BPL OMEGAE HEAVE PITCH BEND)
  923 FORMAT(64xI8)
C     SHIP-AND WATER-CHARACTERISTICS
      PI=3.1415926
 1001 READ 900,N,BPL,GAMMA,GRAV,DISPL
      PRINT 900,N,BPL,GAMMA,GRAV,DISPL
      RO=GAMMA/GRAV
      FN=N
      DXI=BPL/FN
      M=N+1
 1002 READ 901,(BSTAR(I),SECOE(I),DRAFT(I),I=I,M)
      PRINT 901,(BSTAR(I),SECOE(I),DRAFT(I),I=1,M)
      J=M
      TMASS=DISPL/GRAV
  916 FORMAT(32H ENTER RADGYR AND OTHER DATA NOW)
 1013 PRINT 916
 1003 READ 905, RADGYR,XI(1)
      PRINT 905, RADGYR,XI(1)
      IF(RADGYR) 2,2,5
    2 DO 3 I=1,M
 1004 READ 902, DWEIGH(I)
      PRINT 902, DWEIGH(I)
    3 DMASS(I)=DWEIGH(I)/GRAV
      HOMENT=0.0
      DO 4 I=1,M
      L=I-1
      FL=L
    4 HOMENT=HOMENT+DWEIGH(I)*FL
      XI(1)=DXI*HOMENT/DISPL
```

```
   5 DO 6 I=2,M
     L+I-1
     FL=L
   6 XI(I)=XI(1)-DXI*FL
     IF(RADGYR)7,7,9
   7 YNERT=0.0
     DO 8 I=1,M
   8 YNERT=YNERT+DWEIGH(I)*(XI(I)*XI(I)+(DXI*DXI(12.))
   9 YNERT=DISPL*RADGYR*RADGYR
1005 READ 907, MINKRI,MAXKRI,INCRES
     PRINT 907, MINKRI,MAXKRI,INCRES
1006 READ 906, WA,SWL,BWL,DELWL,VMIN,VMAX,DELV
     PRINT 906, WA,SWL,BWL,DELWL,VMIN,VMAX,DELV
     PRINT 909
     V=VMIN
  11 WL=SWL
  12 IF(MINKRI) 14,14,13
  13 KRIT=MINKRI
  14 WAVEN=2.*PI/WL
     CW=SQRTF(GRAV/WAVEN)
     OMEGAE=WAVEN*ABSF(CW+V)
     CALL ADMAB
     CALL COEFF
     CALL EXCITE
     FTWO=-TI(2)
     EMTWO=-TI(5)
     CALL MOTION
     L=(N/2)+1
     DELTA=DELTA*57.295779
     EPSIL=EPSIL*57.295779
     TNULL=TNULL/(WA*WAVEN)
     ZNULL=ZNULL/WA
     IF(MINKRI) 16,16,15
  15 CALL BENDSH
 921 FORMAT(72H
     1         STATION)
     PRINT 921
     PRINT 923, KRIT
     SHNULL=SHNULL*BPL/(GAMMA*(BSTAR(L)*WA)**2)
     BMNULL=BMNULL/(GAMMA*WA*BSTAR(L)*BPL*BPL)
     ALPHA=ALPHA*57.295779
     BETA=BETA*57.295779
  16 DWL=WL/BPL
     FROUDE=V/SQRTF(GRAV*BPL)
     CONTINUE
     PRINT 903, FROUDE,DWL,OMEGAE,ZNULL,TNULL,BMNULL
     IF(MINKRI) 19,19,17
  17 IF(KRIT-MAXKRI) 18,19,19
  18 KRIT=KRIT+INCRES
     GO TO 15
```

```
19 IF(WL-BWL) 20,21,21
20 WL=WL+DELWL
   TO TO 12
21 IF(ABSF(V)-ABSF(VMAX)) 22,25,25
22 V=V+DELV
   GO TO 11
25 CONTINUE
   GO TO 1013
   END(1,0,0,0,0,0,0,0,0,1,0,0,0,0,0,)
```

```
      SUBROUTINE ADMAB
      DIMENSION Y(21),TR(6),TI(6),ADDA(4),BEEB(4),CGGC(4),UR(6),UI(6),
     1DMASS(21),QUANT(21),SKLAM(21),BSTAR(21),CXFST(21),SXFST(21),
     2CTFST(21),STFST(21),XI(21),DIX(21),ENOXI(21),DRAFT(21),DWEIGH(21),
     3SECOE(21),ABAR(21)
      DIMENSION SY(10),SZ(10),SSB(10),SPB(10),SDB(10),SSA(10),SPA(10)
      DIMENSION SLW(10),SDA(10),EPA(5,6),EQA(5,6),EPB(5),EPC(5),EPX(5)
      DIMENSION EQX(5),EPY(5),EQY(5)
      COMMON Y,SYMPS,DXI,ADDA,BEEB,CGGC,ZREAL,ZIMAG,TREAL,TIMAG,ZNULL,
     1TNULL,DELTA,EPSIL,TR,TI,V,DMASS,QUANT,OMEGAE,SKLAM,KRIT,RO,GRAV,
     2BSTAR,CXFST,SXFST,ALPHA,SHNULL,XI,BETA,BMNULL,GAMMA,DIX,M,WA,WAVEN
     3,CW,ENCXI,SIGMA,TAU,FNULL,EMNULL,DRAFT,DWEIGH,SECOE,TMASS,N,UR,UI,
     4ABAR,PI,SHREAL,SHIMAG,BMREAL,BMIMAC,YNERT,BPL
      DO 7499 I=1,M
      SFRPA=((OMEGAE**2)/(2.*GRAV))*BSTAR(I)
      IF(SFRPA) 7001,7001,7002
 7001 QUANT(I)=0.0
      ABAR(I)=0.0
      GO TO 7499
 7002 SBBB=SECOE(I)
      SBB=BSTAR(I)
      SBH=BSTAR(I)/(2.*DRAFT(I))
      SFRPB=SFRPA
 7003 SAN=3.14159+(SBBB*4.0-3.14159)*SBH/(SBH+1.0)**2                001
      SWA=5.55165-1.57078*SAN
      SAZN=(2.35619+SQRTF(SWA))/SAN
      SA=(SBH-1.0)*SAZN/(SBH+1.0)
      SB=SAZN-1.0
      SW=SFRPA/(1.0+SA+SB)
 8003 SYO=SFRPA
      SSBO=3.14159*SINF(SYO)
      SSAO=SINF(SYO)*LOGF(1.781*SYO)-1.57078*COSF(SYO)-SYO
      SSAO=SSAO+0.30556*SYO**3-0.01903*SYO**5
      SFP1=0.0
      SFQ1=0.0
      SQ=-0.05236
      SWF=0.0
      SLWM=0.0
      DO 8004 LS=1,10
      SLS=LS
      SLSP=SLS*0.15708
      SNSL=SINF(SLSP)
      SN3SL=SINF(3.0*SLSP)
      SZ(LS)=SW*((1.0-SA)*SNSL-SB*SN3SL)
      SEZ=3.14159/EXPF(SZ(LS))
      SSB(LS)=SEZ*SINF(SY(LS))
      SPB(LS)=SEZ*COSF(SY(LS))
      SDB(LS)=SSB(LS)-SSBO*(1.0-SLS/10.0)
      SY2=SY(LS)*SY(LS)
      SY3=SY2*SY(LS)
      SZ2=SZ(LS)*SZ(LS)
      SZ3=SZ2*SZ(LS)
      SYZ=SY(LS)*SZ(LS)
      SLOG=0.31831*LOGF(1.781*SQRTF(SY2+SZ2))
      STAN=0.50-0.31831*ATANF(SZ(LS)/SY(LS))
      SSA(LS)=SSB(LS)*SLOG-SPB(LS)*STAN-SY(LS)*(1.0+0.91667*SZ2)     004
```

```
      SSA(LS)=SSA(LS)+SY3*(0.30556+0.01903*(10.0*SZ2-SY2))             004
      SSA(LS)=SSA(LS)+SYZ*(1.5-0.09514*SZ3+0.34722*(SZ2-SY2))
      SPA(LS)=SPB(LS)*SLOG+SSB(LS)*STAN+SZ(LS)*(1.0-0.91667*SY2)       004
      SPA(LS)=SPA(LS)+SZ3*(0.30556-0.08681*SZ(LS)+0.01903*(SZ2-10.*SY2))   004
      SPA(LS)=SPA(LS)+SYZ*(0.09514*SY3)-0.75*SZ2
      SPA(LS)=SPA(LS)+SY2*(0.75-0.08681*SY2+0.52083*SZ2)
      SDA(LS)=SSA(LS)-SSA0*(1.0-SLS/10.0)
      SQ=-SQ
      SFM=((1.0+SA)*SNSL+3.0*SB*SN3SL)*(0.15708+SQ)
      SFQ1=SFQ1+SPB(LS)*SFM
      SFP1=SFP1+SPA(LS)*SFM
      SWF=SWF+SFM/EXPF(SZ(LS)*SFRPB/SFRPA)
      SLWN=SFM*SEZ/(6.28318+40.0*SQ)
      SLW(LS)=SLWM+SLWN
      SLWM=SLW(LS)+SLWN
 8004 CONTINUE
      DO 8010 LS=1,9
      SLS=LS
 8010 SLW(LS)=SLW(10)*SLS/10.0-SLW(LS)
      SFQ1=SFQ1-0.50*SPB(10)*SFM
      SFP1=SFP1-0.50*SPA(10)*SFM
      EPA(1,1)=SSA0
      EQA(1,1)=SSB0
      EPC(1)=SLW(10)
      SQ=-0.05236
      DO 8005 KS=2,5
      EPA(KS,1)=0.0
      EQA(KS,1)=0.0
      EPC(KS)=0.0
      SK=(KS-1)*2
      SQ=-0.05236
      DO 8005 MS=1,9
      SQ=-SQ
      SM=MS
      SMSIN=1.27324*(0.15708+SQ)*SINF(SK*SM*0.15708)
      EPA(KS,1)=EPA(KS,1)+SDA(MS)*SMSIN
      EQA(KS,1)=EQA(KS,1)+SDB(MS)*SMSIN
      EPC(KS)=EPC(KS)+SLW(MS)*SMSIN
 8005 CONTINUE
      SAA=SA*SA+3.0*SB
      SAAA=SA*SAA+3.0*SA*SB
      EPA(1,2)=-SW
      EPA(2,2)=-1.0-0.21221*SW
      EPA(3,2)=-SA-0.02122*SW
      EPA(4,2)=-SAA-0.00606*SW
      EPA(5,2)=-SAAA-0.00253*SW
      EPA(1,3)=-0.33333*SW
      EPA(2,3)=0.38197*SW
      EPA(3,3)=-1.0-0.13642*SW
      EPA(4,3)=-SA-0.02358*SW
      EPA(5,3)=-SAA-0.00868*SW
      EPA(1,4)=-0.20*SW
      EPA(2,4)=0.15158*SW
      EPA(3,4)=0.17684*SW
      EPA(4,4)=-1.0-0.09646*SW
      EPA(5,4)=-SA-0.02040*SW
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```
      EPA(1,5)=-0.1429*SW
      EPA(2,5)=0.09903*SW
      EPA(3,5)=0.06752*SW
      EPA(4,5)=0.11427*SW
      EPA(5,5)=-1.0-0.07428*SW
      EPB(1)=1.0+SA+SB
      EPB(2)=0.63662*(0.33333*(1.0+SA)-1.80*SB)
      EPB(3)=0.31831*(0.06667+0.06667*SA+1.28571*SB)
      EPB(4)=0.63662*(0.00952+0.00952*SA+0.11111*SB)
      EPB(5)=0.31831*(0.00793+0.00793*SA+0.08182*SB)
      DO 8006 KS=1,5
      DO 8006 LS=2,5
 8006 EQA(KS,LS)=0.0
      NEQ=5
 9903 IEPB=7070
      NEP=NEQ+1
      DO 9933 IEQ=1,NEQ
      DO 9948 LEQ=1,NEQ
      EPA(LEQ,NEP)=0.0
 9948 EQA(LEQ,NEP)=0.0
      EPA(IEQ,NEP)=1.0
      IEQY=1
      IF(EPA(IEQ,1))9934,9931,9934
 9931 IF(EQA(IEQ,1))9934,9910,9934
 9934 EQP=EPA(IEQ,1)*EPA(IEQ,1)+EQA(IEQ,1)*EQA(IEQ,1)
      EPT1=EPA(IEQ,1)
      EQT1=EQA(IEQ,1)
      DO 9935 JEQ=1,NEP
      EPT=(EPA(IEQ,JEQ)*EPT1+EQA(IEQ,JEQ)*EQT1)/EQP
      EQT=(EQA(IEQ,JEQ)*EPT1-EPA(IEQ,JEQ)*EQT1)/EQP
      EPA(IEQ,JEQ)=EPT
 9935 EQA(IEQ,JEQ)=EQT
      IEQX=0
      IEQY=2
      IF(IEQ-NEQ)9937,9938,9910
 9938 MEQX=IEQ-1
      MEQY=1
      GO TO 9939
 9937 MEQY=IEQ+1
      MEQX=NEQ
 9939 DO 9940 LEQ=MEQY,MEQX
      IEQX=IEQX+1
      EQP=EPA(LEQ,1)
      EPQ=EQA(LEQ,1)
      DO 9940 JEQ=1,NEP
      EPT=EPA(IEQ,JEQ)*EQP-EQA(IEQ,JEQ)*EPQ
      EQT=EPA(IEQ,JEQ)*EPQ+EQA(IEQ,JEQ)*EQP
      EPA(LEQ,JEQ)=EPA(LEQ,JEQ)-EPT
 9940 EQA(LEQ,JEQ)=EQA(LEQ,JEQ)-EQT
      IEQY=3
      IF(IEQ-1)9910,9944,9945
 9945 IF((NEQ-1)-IEQX)9910,9944,9938
 9944 DO 9946 LEQ=1,NEQ
      DO 9946 JEQ=1,NEQ
      NEQU=JEQ+1
      EPA(LEQ,JEQ)=EPA(LEQ,NEQU)
```

```
9946 EQA(LEC,JEQ)=EQA(LEQ,NEQU)
9933 CONTINUE
9952 DO 9953 IEQ=1,NEQ
     EPX(IEC)*0.0
     EQX(IEC)=0.0
     EPY(IEC)=0.0
     EQY(IEC)=0.0
     DO 9953 JEQ=1,NEQ
     EPX(IEC)=EPX(IEQ)+EPA(IEQ,JEQ)*EPB(JEQ)
     EQX(IEC)=EQX(IEQ)+EQA(IEQ,JEQ)*EPB(JEQ)
     EPY(IEC)=EPY(IEQ)+EPA(IEQ,JEQ)*EPC(JEQ)
     EQY(IEC)=EQY(IEQ)+EQA(IEQ,JEQ)*EPC(JEQ)
9953 CONTINUE
     GO TO 8009
9906 FORMAT(81H THIS SUBROUTINE ADMAB IS NOT ABLE TO FIND THE ADDED MAS
    1S AND CAMPING COEFFICIENT)
9910 PRINT 9906
     GO TO 7499
8009 SF10=9.0*SB*(0.2-0.14286*SA-0.03704*SAA-0.01818*SAAA)
     SF10=SF10-((1.0+SA)*(0.3333+0.06667*SA+0.02857*SAA+0.01587*SAAA))     017
     SF1=SF10-SW*(1.0+SA)*0.78540
     SF20=-(1.0+SA)*(0.06667+0.02857*SA+0.01587*SAA)
     SF20=SF20-9.0*SB*(0.14286+0.03704*SA+0.01818*SAA)
     SF2=SF20-SW*0.78540*SB
     SF3=-(1.0+SA)*(0.02857+0.01587*SA)-9.0*SB*(0.03704+0.01818*SA)
     SF4=-(1.0+SA)*0.01587-9.0*SB*0.01818
     SPF=EPX(1)*SFP1-EQX(1)*SFQ1+EPX(2)*SF1+EPX(3)*SF2+EPX(4)*SF3
     SPF=SPF+EPX(5)*SF4
     SC=SPF/(0.7854*(1.0+SA+SB)**2)
     SAR=3.14159*SW*SQRTF(EPX(1)**2+EQX(1)**2)
     QUANT(I)=SC*(PI*(BSTAR(I)**2)*RO/8.)
9999 ABAR(I)=SAR
7499 CONTINUE
     RETURN
     END(1,0,0,0,0,0,1,0,0,1,0,0,0,0,0)

JOB TIME =   0.11 MIN.
```

```
      SUBROUTINE COEFF
      DIMENSION Y(21),TR(6),TI(6),ADDA(4),BEEB(4),CGGC(4),UR(6),UI(6),
     1DMASS(21),QUANT(21,30),SKLAM(21),BSTA (21),CXFST(21),SXFST(21),
     2CTFST(21),STFST(21),XI(21),DIX(21), NOXI(21),DRAFT(21),DWEIGH(21),
     3SECOE(21),ABAR(21,30),WL(3 ),V(10),FR QL(21,30),ABARN(21 ,30),
     4ADMASN(21,30)
      COMMON Y,J,SYMPS,DXI,ADDA,BEEB,CGGC,ZREAL,ZIMAG,TREAL,TIMAG,ZNULL,
     1TNULL,DELTA,EPSIL,TR,TI,V,DMASS,QUANT,OMEGAE,SKLAM,KRIT,RO,GRAV,
     2BSTAR,CXFST,SXFST,ALPHA,SHNULL,XI,BETA,BMNULL,GAMMA,DIX,M,WA,WAVEN
     3,CW,ENOXI,SIGMA,TAU,FNULL,FMNULL,DRAFT,DWEIGH,SECOE,TMASS,N,UR,UI,
     4ABAR,PI,SHREAL,SHIMAG,BMREAL,BMIMAG,YNERT,BPL,FREQL,ABARN,
     5ADMASN,NSTA,K
C     SMALL A = ADDA(1)
      J=M
      DO 10 I=1,M
   10 Y(I)=QUANT(I,K)
      CALL SIMPS
      ADMAS=SYMPS
      ADDA(1)=ADMAS+TMASS
C     CAPITAL A = ADDA(4)
      DO 21 I=1,M
   21 Y(I)=QUANT(I,K)*(XI(I)**2)
      CALL SIMPS
      ADDA(4)=SYMPS+YNERT/GRAV
C     SMALL D = ADDA(3) = CAPITAL D = ADDA( )
      DO 30 I=1,M
   30 Y(I)=QUANT(I,K)*XI(I)
      CALL SIMPS
      ADDA(2)=SYMPS
      ADDA(3)=ADDA(2)
C     SMALL B = BEEB(1)
      DO 40 I=1,M
      ENOXI(I)=(GAMMA*GRAV*(ABAR(I,K)**2))/(OMEGAE**3)
   40 Y(I)=ENOXI(I)
      CALL SIMPS
      BEEB(1)=SYMPS
C     CAPITAL B = BEEB(4)
      DO 50 I=1,M
   50 Y(I)=ENOXI(I)*(XI(I)**2)
      CALL SIMPS
C     TEMPORARILY
      BEEB(4)=SYMPS
      DIX(1)=-QUANT(2,K)/(2.*DXI)
      DIX(M)=QUANT(N,K)/(2.*DXI)
      DO 55 I=2,N
   55 DIX(I)=(QUANT(I-1,K)-QUANT(I+1,K))/(2.*DXI)
      DO 56 I=1,M
   56 Y(I)=DIX(I)*XI(I)*XI(I)
      CALL SIMPS
      BEEB(4)=BEEB(4)-ABSF(V)*(2.*ADDA(2)+SYMPS)
C     CAPITAL E = BEEB(3)
      DO 60 I=1,M
   60 Y(I)=DIX(I)*XI(I)
      CALL SIMPS
      ETHRE=SYMPS*(ABSF(V))
      DO 63 I=1,M
```

```
   63 Y(I)=ENOXI(I)*XI(I)
      CALL SIMPS
      EONE=SYMPS
      ETWO=2.*(ABSF(V))*ADMAS
      BEEB(3)=EONE-ETHRE
C     SMALL E = BEEB(2)
      BEEB(2)=BEEB(3)-ETWO
C     SMALL C =CGGC(1)
      DO 70 I=1,M
   70 Y(I)=BSTAR(I)
      CALL SIMPS
      CGGC(1)=GAMMA*SYMPS
C     CAPITAL C = CGGC(4)
      DO 71 I=1,M
   71 Y(I)=BSTAR(I)*(XI(I)**2)
      CALL SIMPS
      CGGC(4)=GAMMA*SYMPS-(ABSF(V))*BEEB( )
C     CAPITAL G = CGGC(3)
      DO 80 I=1,M
   80 Y(I)=BSTAR(I)*XI(I)
      CALL SIMPS
      CGGC(3)=SYMPS*GAMMA
C     SMALL G = CGGC(2)
      CGGC(2)=CGGC(3)-(ABSF(V))*BEEB(1)
      RETURN
      END(1,1,0,0,0,0,1,1,0,1,0, ,0,0,0)

JOB TIME =   0.37 MIN.
```

```
      SUBROUTINE EXCITE
      DIMENSION Y(21),TR(6),TI(6),ADDA(4),B EB(4),CGG (4),UR( ),UI(6),
     1DMASS(21),QUANT(21,30),SKL M(21),BSIA (21),CXFSI(21),SXFST(21),
     2CTFST(21),STFST(21),XI(21),DIX(21), N XI(21),DRAFT( 1),DWEIGH(21),
     3SECOE(21),ABAR(21,30),WL(3 ),V(20),FR QL(21,30),ABARN(  ,30),
     4ADMASN(21,30)
      COMMON Y,J,SYMPS,DXI,ADDA, EEB,CGGC,Z EAL,ZIMAG,TREAL,TIMAG,ZNULL,
     1TNULL,DELTA,EPSIL,TR,TI,V,DMASS,QUA T,OMEGAE,SKLAM,KRIT,RO,GRAV,
     2BSTAR,CXFST,SXFST,ALPHA,SHNULL,XI,B T ,BMNULL,GAMMA,DIX,M,W ,WAVEN
     3,CW,ENOXI,SIGMA,TAU,FNULL,EMNULL,DRAFI,DWEIGH,S COE,TMASS,N,UR,UI,
     4ABAR,PI,SHREAL,SHIMAG,BMREAL,BMIMAG,Y ERT,BPL,F EQL,ABARN,
     5ADMASN,NSTA,K
      J=M
      DO 90 I=1,M
      FKLAM=(GAMMA*BSTAR(I)-((WAVEN*CW)**  )*QUANT(I,K))*WA
      SKLAM(I)=ENOXI(I)-(DIX(I)*ABSF(V))
      CXFST(I)=(FKLAM*SINF(WAVEN*XI(I))+(WAVEN*CW*WA)*SKLAM(I)
     1*COSF(WAVEN*XI(I)))*(EXPF(-WAVEN*DRAF (I)*SECOF(I)))
      SXFST(I)=(FKLAM*COSF(WAVEN*XI(I))-(WAVEN*CW*WA)*SKLAM(I)
     1*SINF(WAVEN*XI(I)))*(EXPF(-WAVEN*DRAFT(I)*SECO (I)))
   90 Y(I)=CXFST(I)
      CALL SIMPS
C     FONE
      TR(2)=SYMPS
      DO 92 I=1,M
   92 Y(I)=SXFST(I)
      CALL SIMPS
C     -FTWO
      TI(2)=-SYMPS
      DO 93 I=1,M
   93 Y(I)=CXFST(I)*XI(I)
      CALL SIMPS
C     EMONE
      TR(5)=SYMPS
      DO 94 I=1,M
   94 Y(I)=SXFST(I)*XI(I)
      CALL SIMPS
C     -EMTWO
      TI(5)=-SYMPS
      SIGMA=ATANF(-TI(2)/TR(2))
      TAU=ATANF(-TI(5)/TR(5))
      FNULL=SQRTF(TR(2)**2+TI(2)**2)
      EMNULL=SQRTF(TI(5)**2+TR(5)**2)
      RETURN
      END(1,1,0,0,0,0,1,1,0,1,0, ,0,0,0)

JOB TIME =  01.20 MIN.
```

```
      SUBROUTINE MOTION
      DIMENSION Y(21),TR(6),TI(6),ADDA(4),BEEB(4),CGGC(4),UR(6),UI(6),
     1DMASS(21),QUANT(21,30),SKLAM(21),BSTAR(21),CXFST(21),SXFST(21),
     2CTFST(21),STFST(21),XI(21),DIX(21),ENOXI(21),DRAFT(21),DWEIGH(21),
     3SECOE(21),ABAR(21,30),WL(30),V(30),FREQL(21,30),ABARN(21,30),
     4ADMASN(21,30)
      COMMON Y,J,SYMPS,DXI,ADDA,BEEB,CGGC,ZREAL,ZIMAG,TREAL,TIMAG,ZNULL,
     1TNULL,DELTA,EPSIL,TR,TI,V,DMASS,QUANT,OMEGAE,SKLAM,KRIT,RO,GRAV,
     2BSTAR,CXFST,SXFST,ALPHA,SHNULL,XI,BETA,BMNULL,GAMMA,DIX,M,WA,WAVEN
     3,CW,ENOXI,SIGMA,TAU,FNULL,EMNULL,DRAFT,DWEIGH,SECOE,TMASS,N,UR,UI,
     4ABAR,PI,SHREAL,SHIMAG,BMREAL,BMIMAG,YVERT,BPL,FREQL,ABARN,
     5ADMASN,NSTA
      DO 105 J=1,4
      GO TO (100,101,102,103), J
  100 I=1
      GO TO 104
  101 I=3
      GO TO 104
  102 I=4
      GO TO 104
  103 I=6
  104 TR(I)=CGGC(J)-ADDA(J)*(OMEGAE**2)
  105 TI(I)=BEEB(J)*OMEGAE
      DO 110 I=2,3
      DO 110 K=1,2
      IF(K*I-4) 108,110,108
  108 IPK=I+K
      UR(IPK)=TR(I)*TR(K+3)-TI(I)*TI(K+3)-TR(K)*TR(I+3)+TI(K)*TI(I+3)
      UI(IPK)=TR(I)*TI(K+3)+TI(I)*TR(K+3)-TR(K)*TI(I+3)-TI(K)*TR(I+3)
  110 CONTINUE
      DO 111 I=1,6
      UR(I)=UR(I)/10000000000.
  111 UI(I)=UI(I)/10000000000.
      DENUM=UR(4)**2+UI(4)**2
      ZREAL=(UR(5)*UR(4)+UI(5)*UI(4))/DENUM
      ZIMAG=(UR(5)*UI(4)-UI(5)*UR(4))/DENUM
      TREAL=(UR(3)*UR(4)+UI(3)*UI(4))/DENUM
      TIMAG=(UR(3)*UI(4)-UI(3)*UR(4))/DENUM
      ZNULL=SQRTF(ZREAL**2+ZIMAG**2)
      TNULL=SQRTF(TREAL**2+TIMAG**2)
      DELTA=ATANF(ZIMAG/ZREAL)
      EPSIL=ATANF(TIMAG/TREAL)
      RETURN
      END(1,1,0,0,0,0,1,1,0,1,0,0,0,0,0)

JOB TIME =   0.83 MIN.
```

```
      SUBROUTINE BENDSH
      DIMENSION Y(21),TR(6),TI(6),ADDA(4),BEEB(4),CGGC(4),UR(6),UI(6),
     1DMASS(21),QUANT(21),SKLAM(21),BSTAR(21),CXFST(21),SXFST(21),
     2CTFST(21),STFST(21),XI(21),DIX(21),ENOXI(21),DRAFT(21),DWEIGH(21),
     3SECOE(21),ABAR(21),ACREAL(21),ACIMAG(21)
      COMMON Y,J,SYMPS,DXI,ADDA,BEEB,CGGC,ZREAL,ZIMAG,TREAL,TIMAG,ZNULL,
     1TNULL,CELTA,EPSIL,TR,TI,V,DMASS,QUANT,OMEGAE,SKLAM,KRIT,RO,GRAV,
     2BSTAR,CXFST,SXFST,ALPHA,SHNULL,XI,BETA,BMNULL,GAMMA,DIX,MWWA,WAVEN
     3,CW,ENCXI,SIGMA,TAU,FNULL,EMNULL,DRAFT,DWEIGH,SECOE,TMASS,N,UR,UI,
     4ABAR,PI,SHREAL,SHIMAG,BMREAL,BMIMAG,YNERT,BPL
      X=(-1.)**KRIT
      IF(X) 111,111,112
  111 J=KRIT
      GO TO 113
  112 J=KRIT+1
  113 JENS=KRIT+1
      DO 114 I=1,JENS
      ACREAL(I)=(ZREAL+TREAL*XI(I))*(OMEGAE**2)
      ACIMAG(I)=(ZIMAG+TIMAG*XI(I))*(OMEGAE**2)
      CTFST(I)=ACREAL(I)*QUANT(I)
     1+(QUANT(I)*2.*ABSF(V)*OMEGAE)*TIMAG-SKLAM(I)*(((ZIMAG+TIMAG*
     2XI(I))*OMEGAE)-ABSF(V)*TREAL)-(GAMMA*BSTAR(I))*(ZREAL+TREAL*XI(I))
     3+CXFST(I)
      STFST(I)=ACIMAG(I)*QUANT(I)
     1-(QUANT(I)*2.*ABSF(V)*OMEGAE)*TREAL+SKLAM(I)*(((ZREAL+TREAL*
     2XI(I))*OMEGAE)+ABSF(V)*TIMAG)-(GAMMA*BSTAR(I))*(ZIMAG+TIMAG*XI(I))
     3+SXFST(I)
  114 Y(I)=CTFST(I)
      CALL SIMPS
      SHREAL=0.
      DO 200 I=1,J
  200 SHREAL=SHREAL+ACREAL(I)*DMASS(I)
      SHREAL=SHREAL-(X*ACREAL(JENS)*DMASS(JENS)/2.)
      SHREAL=SYMPS-(X*CTFST(KRIT+1)*DXI/2.)+SHREAL
  117 DO 118 I=1,J
  118 Y(I)=STFST(I)
      CALL SIMPS
      SHIMAG=0.
      DO 250 I=1,J
  250 SHIMAG=SHIMAG+ACIMAG(I)*DMASS(I)
      SHIMAG=SHIMAG-X*ACIMAG(JENS)*DMASS(JENS)/2.
      SHIMAG=SYMPS-(X*STFST(KRIT+1)*DXI/2.)+SHIMAG
  121 ALPHA=ATANF(SHIMAG/SHREAL)
      SHNULL=SQRTF(SHREAL**2+SHIMAG**2)
      DO 122 I=1,J
  122 Y(I)=CTFST(I)*(XI(I)-XI(KRIT+1))
      CALL SIMPS
      BMREAL=0.
      DO 300 I=1,J
  300 BMREAL=BMREAL+ACREAL(I)*DMASS(I)*(XI(I)-XI(JENS))
      BMREAL=BMREAL+ACREAL(JENS)*DMASS(JENS)*DXI/8.
      BMREAL=SYMPS+(CTFST(KRIT+1)*DXI*DXI/8.)+BMREAL
  125 DO 126 I=1,J
  126 Y(I)=STFST(I)*(XI(I)-XI(KRIT+1))
      CALL SIMPS
      BMIMAG=0.
```

```
      DO 350 I=1,J
  350 BMIMAG=BMIMAG+ACIMAG(I)*DMASS(I)*(XI(I)-XI(JENS))
      BMIMAG=BMIMAG+ACIMAG(JENS)*DMASS(JENS)*DXI/8.
      BMIMAG=SYMPS+(STFST(KRIT+1)*DXI*DXI/8.)+BMIMAG
  129 BETA=ATANF(BMIMAG/BMREAL)
      BMNULL=SQRTF(BMREAL**2+BMIMAG**2)
      RETURN
      END(1,0,0,0,0,0,0,0,0,1,0,0,0,0,0)
```

JOB TIME =   .05 MIN.

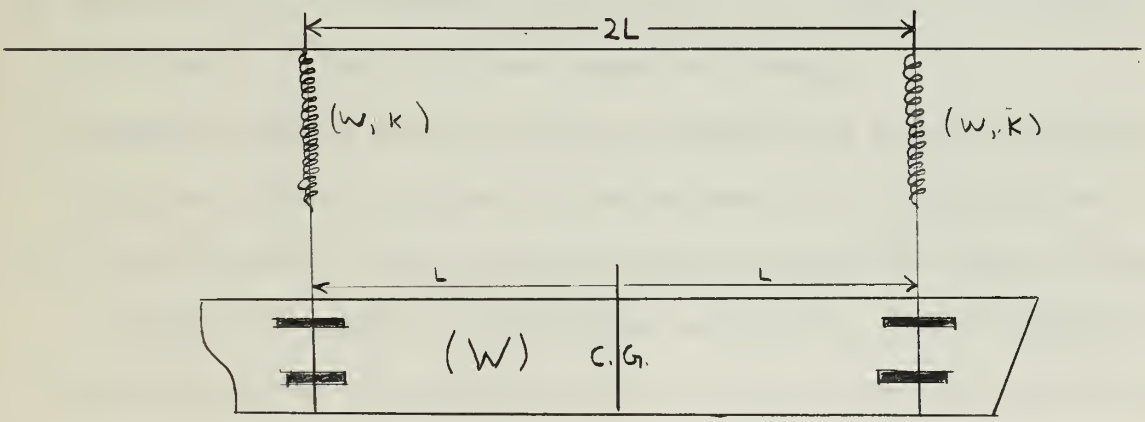

```
      SUBROUTINE SIMPS
      DIMENSION Y(21),TR(6),TI(6),ADDA(4),BEEB(4),CGGC(4),UR(6),UI(6),
     1DMASS(21),QUANT(21,30),SKLAM(21),BSTAR(21),CXFST(21),SXFST(21),
     2CTFST(21),STFST(21),XI(21),DIX(21),ENOXI(21),DRAFT(21),DWEIGH(21),
     3SECOE(21),ABAR(21,30),WL(30),V(20),FREQL(21,30),ABARN(21,30),
     4ADMASN(21,30)
      COMMON Y,J,SYMPS,DXI,ADDA,BEEB,CGGC,ZREAL,ZIMAG,TREAL,TIMAG,ZNULL,
     1TNULL,DELTA,EPSIL,TR,TI,V,DMASS,QUANT,OMEGAE,SKLAM,KRIT,RO,GRAV,
     2BSTAR,CXFST,SXFST,ALPHA,SHNULL,XI,BETA,BMNULL,GAMMA,DIX,M,WA,WAVEN
     3,CW,ENOXI,SIGMA,TAU,FNULL,EMNULL,DRAFT,DWEIGH,SECOE,IMASS,N,UR,UI,
     4ABAR,PI,SHREAL,SHIMAG,BMREAL,BMIMAG,YVERT,BPL,FREQL,ABARN,
     5ADMASN,NSTA,K
      SUM=Y(1)+Y(J)
      KARL=J-1
      DO 151 I=2,KARL
      X=(-1.)**I
      IF(X) 151,150,150
  150 Y(I)=2.*Y(I)
  151 SUM=SUM+2.*Y(I)
      SYMPS=(DXI/3.)*SUM
      RETURN
      END(1,1,0,0,0,0,1,1,0,1,0,0,0,0,0)
```

JOB TIME = 01.56 MIN.

APPENDIX D

MODEL RADIUS OF GYRATION

The procedure used to determine the radius of gyration of the models is described. No information was available on the full scale radius of gyration for the catamaran or ALVIN. Therefore the radius of gyration was assumed to be 0.25 of the length. Because of the small weight of ALVIN compared to weight of instrumentation, which had to be positioned at the center of gravity, the largest radius of gyration that could be obtained was 0.232 of the length. The catamaran model was constructed with built-in lead ballast, and even with a drastic alteration of the model, the largest radius of gyration was 0.189 of the length.



Equipment:

2 springs of same stiffness k

1 stopwatch

string, tape, set of ballast weights

Procedure:

a) Suspend the two springs from the clamps which are attached to convenient points on the ceiling. The distance between the two springs should be 2L.

b) Make sure the ship model, without ballast, rests on level keel (or at desired trim) when put in water, and determine the center of gravity of the model. Assume that the center of gravity coincides with the center of flotation. Now put all ballast in model symmetrically about the C.G.

c) Measure off the distance L on each side of the center of gravity of the ship model. L can be of any convenient length.

d) Suspend the model from the springs, using string wrapped around the model and secured in place by tape as shown in the figure above.

e) Force the model to an up and down motion (heave) and count with the stopwatch the number of oscillations per minute. Thus, determine f_H.

f) Force the model to a pitching motion and count with the stopwatch the number of oscillations per minute. Thus determine f_p. It is not necessary to achieve a pure pitching motion, completely uncoupled from heave, because the period of heave does not affect the period of pitch.

g) Let W be the weight of the ship and w the weight of each of the springs. The moment of inertia of the system can be approximated by:

$$I_s = (W+w)k_s^2 \quad \text{and} \quad I_s = Wk_g^2+wL^2 \tag{13}$$

where k_s and k_g are the radius of gyration of the system and the model, respectively.

Therefore: $$k_g^2 = \frac{W+w}{W} k_s^2 - \frac{w}{W} L^2 \tag{14}$$

The radius of gyration of the system is given by:

$$k_s = \frac{f_H}{f_p} L, \text{ since } f_H = \frac{2k}{M} \ \& \ f_p = \frac{2k}{M} \frac{L}{k_s} \tag{15}$$

where M is the mass of the system and k the stiffness of each spring.

Hence,

$$k_g^2 = [\frac{W+w}{W} (\frac{f_H}{f_p})^2 - \frac{w}{W}]L^2 \tag{16}$$

For a given weight of model, the heaving period f_H remains constant. So, we can change the $\frac{f_H}{f_p}$ ratio by changing the pitching period. To increase f_p, dispose ballast weights closer to C.G., making sure they are still symmetrically disposed about the C.G. To decrease f_p, dispose ballast weights further away from the C.G. When $\frac{f_H}{f_p}$ equals the value given from the above relation, the ballasting procedure of the ship is over.

[illegible]

[illegible]

$$[illegible]$$ [illegible]

[illegible]

$$[illegible]$$

[illegible]

$$[illegible]$$ [illegible]

[illegible]

APPENDIX E

SUMMARY OF EXPERIMENTAL DATA

The following data is a summary of the experimental data obtained at the M.I.T. Ship Model Towing Tank. It represents data read from Sanborn Oscillograph tapes.

The catamaran single hull and catamaran data are for both directly ahead and astern seas. (Tables V-VIII). Table IX is for ALVIN in directly ahead seas and Table X for directly astern seas. Table XI is ALVIN data in directly ahead seas, while in the recovery position. Table XII is ALVIN pitching data and the catamaran heaving data, while in the recovery position.

TABLE V

Catamaran Single Hull Experimental Data, h_o = 0.375 inches				
λ(ft.)	z_o(in)	Θ_o(deg)	z_o/h_o	$\frac{\Theta_o \text{rad})}{Kh_o}$
3.0	0.0	0.125	0.0	0.034
4.0	0.04	0.25	0.1068	0.089
4.5	0.0025	0.5	0.0066	0.200
6.0	0.075	0.5625	0.2000	0.300
10.0	0.1875	0.75	0.5000	0.705

TABLE VI

Catamaran Experimental Data, h_o = 0.375 inches				
λ(ft.)	z_o(in)	Θ_o(deg)	z_o/h_o	$\frac{\Theta_o(\text{rad})}{Kh_o}$
3.0	0.0400	0.25	0.1068	0.067
4.0	0.0250	0.80	0.0667	0.284
4.5	0.0375	0.75	0.1000	0.301
6.0	0.0875	0.625	0.2333	0.333
10.0	0.3000	0.825	0.8000	0.775

TABLE VII

Catamaran Single Hull Experimental Data, h_o = 0.75 inches				
λ(ft.)	z_o(in)	Θ_o(deg)	z_o/h_o	$\frac{\Theta_o\text{(rad)}}{Kh_o}$
3.0	0.0	0.20	0.00	0.027
4.0	0.075	0.75	0.10	0.134
4.5	0.025	1.00	0.334	0.201
6.0	0.1625	1.69	0.2165	0.452
10.0	0.3750	1.375	0.500	0.613

TABLE VIII

Catamaran Experimental Data, h_o = 0.75 inches				
λ(ft.)	z_o(in)	Θ_o(deg)	z_o/h_o	$\frac{\Theta_o\text{(rad)}}{Kh_o}$
3.0	0.10	0.25	0.1333	0.0334
4.0	0.05	1.00	0.0667	0.1780
4.5	0.0625	1.25	0.0834	0.2500
6.0	0.200	2.25	0.2670	0.6000
10.0	0.600	2.00	0.8000	0.8910

TABLE IX

ALVIN Experimental Data, Directly Ahead Seas, h_o = 0.375 inches				
λ(ft.)	z_o(in)	Θ_o(deg)	z_o/h_o	$\frac{\Theta_o(\text{rad})}{Kh_o}$
1.0	.075	0.5	0.2	0.0045
2.0	-	0.6	-	0.1068
3.0	.150	1.5	0.4	0.4000
5.0	.150	2.7	0.4	1.2000
10.0	.08	5.4	0.2135	4.8000

TABLE X

ALVIN Experimental Data, Directly Astern Seas, h_o = 0.375 inches				
λ(ft.)	z_o(in)	Θ_o(deg)	z_o/h_o	$\frac{\Theta_o(\text{rad})}{Kh_o}$
1.0	0.01	0.9	0.0266	0.08
2.0	0.05	0.7	0.133	0.1245
3.0	0.06	1.4	0.160	0.375
5.0	0.13	4.8	0.347	2.12
10.0	-	-	-	-

\- indicates data not obtained

TABLE XI

Recovery Experimental Data Directly Ahead Seas, h_o = 0.375 inches				
λ(ft)	ALVIN z_o(in)	ALVIN Θ_o(deg)	z_o/h_o	$\frac{\Theta_o\text{(rad)}}{Kh_o}$
1.0	0.030	0.60	0.008	0.005
2.0	0.055	1.00	0.0147	0.178
3.0	0.100	4.40	0.0267	1.175
4.5	0.040	1.50	0.0107	0.600
5.0	0.005	2.00	0.0133	0.890
10.0	0.075	5.00	0.0200	4.45

TABLE XII

Recovery Experimental Data Directly Ahead Seas, h_o = 0.375 inches				
λ(ft.)	Cat. z_o(in)	ALVIN Θ_o(deg.)	z_o/h_o	ALVIN $\frac{\Theta_o\text{(rad)}}{Kh_o}$
3.0	0.050	1.7	0.133	0.454
4.0	0.010	1.0	0.027	0.356
4.5	0.025	0.8	0.067	0.320
6.0	0.125	1.6	0.334	0.853
10.0	0.225	2.4	0.600	2.140

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